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DEFORMATION OF ROCKS UNDER HIGH CONFINING PRESSURES[1]

I. EXPERIMENTS AT ROOM TEMPERATURE

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ABSTRACT

A series of experiments was performed to investigate the physical processes underlying rock deformation. The apparatus used took advantage of recent developments in high-pressure technique by Bridgman to carry the range of pressure investigation to four times the amount of confining pressure available in the apparatus of F. D. Adams. Also, an entirely different technique was used, which obviated some of the inherent defects of Adams' apparatus.

The relation between strength and confining pressure was investigated up to 11,000 atmospheres confining pressure. Strength was also investigated as a function of time. The effect of confining pressure on fracture and flow was particularly studied. The effect of deformation on the fabric of a rock is briefly described in the case of marble. Quartz was tested under pressures up to 12,000 atmospheres. Tension and torsion tests under high pressure gave paradoxical results. Plans for future work are discussed.

INTRODUCTION

We have many books filled with geological observations and speculations concerning the behavior of rocks under the conditions of high pressure and temperature which prevail in the outer shell of the earth. We observe their characteristics after they have been plunged deep into the earth, fractured, deformed plastically, metamorphosed, uplifted again, and exposed by erosion. As to the actual physical processes which cause the changes we are pretty much in

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the dark, partly because we cannot tell how many of the processes took place simultaneously, and partly because we can never be sure of the environment in which these changes took place—the conditions of temperature and pressure and the rôle of mineralizing solutions. The most promising method of increasing our knowledge of the physics and chemistry underlying these processes seems to be experimentation in the laboratory, under controlled conditions of pressure and temperature.

Experimental observation of the deformation of rocks under high confining pressures has been greatly neglected since the pioneering work of F. D. Adams.[2] The bulk of the experimental work has been concerned with physico-chemical relations of mineral stability and with compressibility measurements. It seemed important to the writer to check Adams' work and to carry the study of rock deformation to the higher values of confining pressures which are now available in the laboratory.

Adams' experiments demonstrated beautifully the property which he set out to show, namely, that rocks change their character when a confining pressure is applied, so that they are no longer brittle, but behave plastically. His apparatus had inherent defects, however, which made it impossible for him to get more than qualitative measurements of the force necessary to cause deformation and the strength under confining pressure. The apparatus with which he attempted these measurements is sketched in Figure 1.[3] The confining pressure was developed by placing the specimen in a tightly fitting steel jacket, so that in order to deform the specimen the steel jacket had to be deformed. This method has three outstanding defects:

[2] F. D. Adams and J. T. Nicholson, "An Experimental Investigation into the Flow of Marble," *Phil. Trans. Roy. Soc. London*, Ser. A, Vol. CXCV (1901), pp. 363–401; F. D. Adams and E. G. Coker, "Flow of Marble," *Amer. Jour. Sci.*, Vol. XXIX (4th ser., 1910), pp. 465–85; Adams, "An Experimental Investigation into the Action of Differential Pressure on Certain Minerals and Rocks, Employing the Process Suggested by Professor Kick," *Jour. Geol.*, Vol. XVIII (1910), pp. 489–525; "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *ibid.*, Vol. XX (1912), pp. 97–118; F. D. Adams and J. A. Bancroft, "Internal Friction during Deformation and the Relative Plasticity of Different Types of Rocks," *ibid.*, Vol. XXV (1917), pp. 597–637.

[3] Adams and Bancroft, *op. cit.*, p. 602.

(1) it is impossible to measure exactly the confining pressure because of the friction between the jacket and the specimen; (2) since the confining pressure depends on the amount of bulging of the jacket, it increases as the deformation of the specimen increases, hence the confining pressure is sensibly zero at the moment of beginning the deformation; (3) by this method of confining the specimen is not

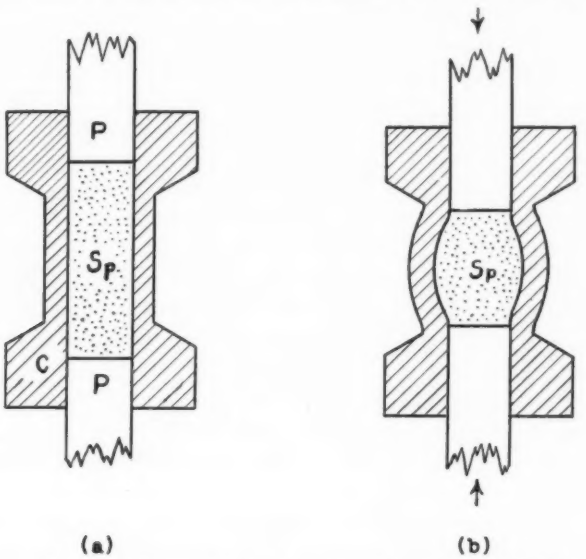


FIG. 1.—Schematic diagram of Adams' apparatus for measuring strength of rocks under high confining pressure: (*a*) before deformation, (*b*) after deformation. Arrows indicate direction of application of pressure.

free to fracture by major shear or tension fractures, since a fracture would have to tear through the walls of the steel jacket.

In undertaking this study an endeavor was made to overcome these defects. The confining pressure is developed in a liquid which surrounds the specimen. This hydrostatic confining pressure may be measured very accurately. To this is added a differential pressure and the resultant shortening of the rock column is measured directly. The apparatus is so designed that the hydrostatic pressure remains constant throughout the deformation. Since the specimen is sur-

rounded only by a liquid of fairly low viscosity, it is free to fracture as in ordinary laboratory tests at atmospheric pressure.

These conditions of testing give values for strength, show changes in the mode of fracture, and permit the study of plasticity in specimens which, by direct comparison with laboratory experiments at atmospheric pressure, show the changes in physical properties caused by the confining pressure. Conditions in the earth's crust are not simulated, however, since any unit of rock in nature is surrounded by other rock. It seems certain that this surrounding rock presents more resistance to fracture of the unit under consideration than would a surrounding liquid. It is equally certain that the surrounding rock does not present so much resistance to fracture as Adams' steel jacket, since the strength of the surrounding rock is not greater than that of the unit considered.

It is difficult to picture the conditions of rupture in the earth's crust. Some geologists have had the idea that all major fractures originate either at the surface of the earth or at a structural discontinuity. In this case, as the fracture is propagated downward, the surrounding rocks offer no resistance to fracture except that due to friction along the fracture surface. Consequently, they would be expected to produce small jacketing effects.

On the other hand, we have abundant evidence in earthquakes whose foci are miles below the surface of the earth that at least some fractures originate at depth, presumably where no surface effects can control the fracture. In this case we must suppose that there is a local concentration of stress at the point where rupture occurs. Now the rock immediately surrounding this point must be under stress which is near its rupture value, since it is inconceivable that any stress in the earth's crust be extremely localized. Consequently, its effect as a confining jacket is small, and the confining pressure it can exert is numerically equal to the difference between the stress on it and its strength under the conditions of pressure which apply at that point.

The writer is greatly indebted to Dr. P. W. Bridgman for constant supervision, suggestions, and discussion of the methods and results. Discussion with Professor R. A. Daly and Professor L. C.

Graton has also been very helpful. E. B. Dane, Jr., has been a constant confrère in matters of technique, and has given valuable assistance during experiments. This work was made possible by a joint grant from the Committee on Geophysical Research and the Society of Fellows of Harvard University.

DESCRIPTION OF APPARATUS

The principles of the apparatus are shown in Figure 2. The high-pressure bomb B has two pistons entering it. The function of the lower piston P_2 is to regulate the hydrostatic pressure on the liquid K (kerosene). This liquid moves freely between the upper and the lower chambers of the bomb by a passageway not shown. The function of the upper piston P_1 is to apply the differential pressure to the specimen S which rests on the fixed platen at the bottom of the upper chamber.

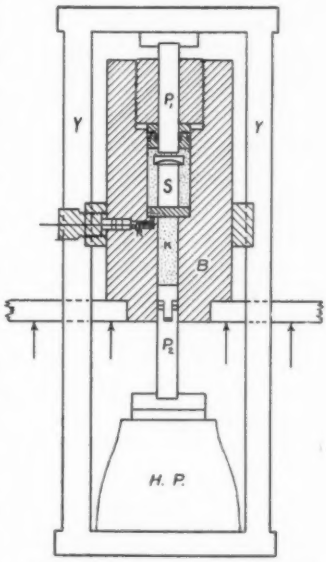


FIG. 2.—Schematic diagram of high-pressure apparatus used by the writer.

In order to keep the hydrostatic pressure constant during the deformation of the specimen, the two pistons P_1 and P_2 are yoked together by Y so that as P_1 is advanced into the bomb, deforming the specimen, P_2 is withdrawn an equal amount. By making the pistons the same diameter, the pressure is thus maintained at a constant value.

The force to compress the liquid is supplied by the small hydraulic press $H.P.$ acting on P_2. The yoked pistons are moved by the main hydraulic press (not shown), which has the effect of forcing the bomb up, as shown by the arrows in the diagram, thus driving P_1 into the bomb.

The method of packing the pistons to avoid leaks, the choice of

steel to withstand the high pressures, and the method of measuring the hydrostatic pressures are taken from Bridgman.[4] The only innovation in the high-pressure technique is the ring packing around the upper piston. This permits the use of a solid piston, so that the deformation of the specimen may be measured directly by measuring the displacement of P_1. This ring packing utilizes the principle of the "unsupported area" and is shown clearly enough in the diagram, so that further discussion is unnecessary. The writer wishes again to acknowledge his indebtedness to Dr. Bridgman for helpful co-operation in solving all the problems of technique and for the use of his machine-shop facilities.

It is necessary to measure four things: (1) the hydrostatic pressure; (2) the frictional force necessary to cause movement of the yoke containing the two pistons; (3) the differential force on the specimen; and (4) the displacement of the upper piston which gives directly the amount of deformation.

The hydrostatic pressure is measured by the change in resistance of a coil of manganin wire in the gauge R. This is Bridgman's standard pressure indicator.[5] I use his manganin wire, and his calibration. It is checked roughly by a measurement of the force on the lower piston P_2 (accomplished by a gauge on the hydraulic press $H.P.$).

The frictional force is read directly on the gauge of the main hydraulic press. This press is a Southwark-Emery hydraulic press with accuracy of reading to probably better than one-half of 1 per cent. In measuring this friction the upper piston is left about 0.5 cm. above the specimen in assembling the apparatus. Then when the run begins, after the hydrostatic pressure is brought up by P_2, the frictional force is that necessary to bring the upper piston down until it hits the specimen. The friction is the largest source of error, but it can generally be reproduced to within 1–1.5 per cent of the total load on the specimen.

The differential force on the specimen is read from the gauge of the main press by subtracting the frictional force from the total reading. The assumption here is that the friction is unchanged by

[4] P. W. Bridgman, *The Physics of High Pressure* (New York: Macmillan Co., 1931), chaps. ii and iii.

[5] *Ibid.*, pp. 70–75.

the addition of the differential pressure to the piston P_1. This effect cannot be calculated, and there is the possibility that it introduces some error. The writer hopes to be able to perfect a manganin pressure gauge to go inside the bomb and give a direct measure of the differential pressure. So far this attempt has not met with success.

The deformation of the specimen is measured by a micrometer dial gauge on piston P_1. The apparatus is first calibrated with a piece of steel with a known Young's modulus inserted in place of the specimen. This gives the correction due to the contraction of the piston under differential pressure, and also that of the plates above and below the specimen.

The precision of these measurements is as follows: The hydrostatic pressure can be kept constant within 20 atmospheres, or 0.2 per cent at 10,000 atmospheres. The absolute accuracy of pressure measurement is of the order of magnitude of 1 per cent. The differential pressure can be measured relatively to 0.5 per cent, and absolutely to about 2 per cent. The shortening can be measured to 0.05 per cent of the original length of the specimen.

One of the major problems of all compression testing is to provide even distribution of force over the end of the specimen and parallel to its axis. This was done by first cutting the specimen ends very accurately parallel and perpendicular to the sides. The ends are parallel to within 0.0002 inch. Second, a ball-and-socket force-equalizer is used between the specimen and the upper piston. The evenness of deformation of the specimens (e.g., Pl. IV*B*) shows how effective these precautions are.

Another problem in compression testing is the effect of a lubricant between the ends of the specimen and the platens of the press. It has been shown that this has a very important effect on certain materials in tests at atmospheric pressure.[6] Experiments using the photoelastic method of analysis indicated that the stress distribution in the specimen depended very much more on the smoothness and flatness of the ends of the specimen than on lubrication. Because of

[6] A. Nadai, *Plasticity* (New York: McGraw-Hill Book Co., 1931), pp. 120–21; K. K. Welker, "Rock Failure in Deep Mines" (Harvard University Ph D. thesis, 1933), pp. 81–107; K. Hübers, "Das Verhalten einiger technischer Eisenarten beim Druckversuch," *Walzwerkausschussbericht des V.D.E., No. 32* (Düsseldorf).

the difficulties in applying lubricants, it was decided at first to proceed without them. The results indicate that they are entirely unnecessary to produce even stress distribution in tests at high pressures. One reason for this is that the ends of the specimen are exposed to kerosene before the piston P_1 is brought down on the specimen. Kerosene at high pressures is at least as viscous as a heavy engine oil, and probably acts as a very effective lubricant itself. At any rate, deformation with as little bulge as is shown in Plate IV*B* shows that the stress distribution is as even as could be expected with any method of lubrication.

The shape of the specimen is chosen, following the practice of testing engineers, so that shear fractures are not inhibited by the platens, and at the same time buckling does not occur. Experience has shown that a height equal to twice the diameter is the most satisfactory. The shape of the cross section must also be considered. The writer began by using square prisms, as it was thought that the square section would permit better study of Lüders' lines and major shear surfaces. However, the stress distribution is much simpler in circular cylinders, and for other purposes (such as jacketing) the circular cross section is more desirable. Also, when only a few are to be made, the cylinders are much cheaper. For these reasons the bulk of the more recent experiments were performed on cylinders.

The size of the specimen is limited either by the size of the high-pressure chamber in the bomb or by the strength of the specimen. For limestone, marble, etc., the specimen is 1 inch tall and $\frac{1}{2}$ inch in diameter. For quartz single crystals, however, where the strength is very great, the specimens are $\frac{5}{16}$ inch in diameter and $\frac{5}{8}$ inch tall. This size is dictated by the maximum force which can be applied to the specimen, and hence depends on the capacity of the main press and the size of the piston P_1.

The apparatus described so far is adapted only to compressive tests. It seemed desirable to try some tension and torsion tests also, to observe the characteristics under different stress distributions.

In order to get torsional stresses in the specimen, two coaxial cylinders were made with a square hole in the inner one, which was split in two transversely. One of these inner cylinders was keyed to the bomb. The other was fitted over a special piston P_1 which had a

square end. The specimen was square at the ends with the central half turned round. Torsion was developed by rotating the piston P_1. The two coaxial cylinders were a nice fit, so that the two square holes were kept accurately aligned to prevent bending moments. In this way a purely torsional couple was applied to the specimen. The stress in all other directions was hydrostatic.

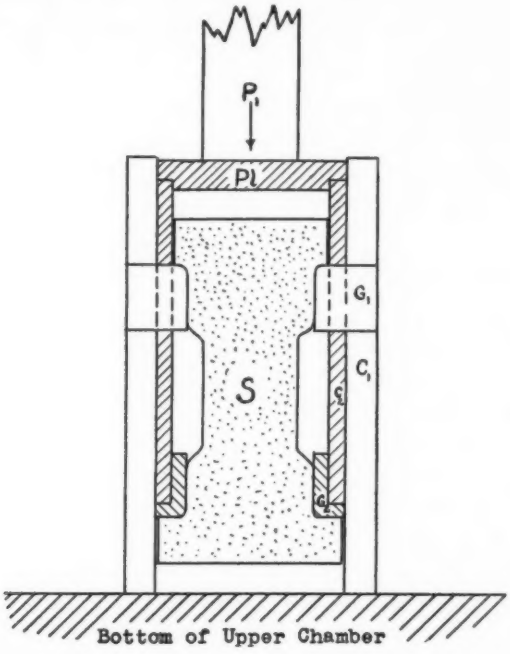


FIG. 3.—Double-yoke apparatus for tension tests under high pressure. This apparatus fits in the high pressure chamber of the bomb in Figure 2.

To set up tension in the specimen, it was necessary to make a double-tension yoke, shown in Figure 3, to convert the compressive force of the piston into an effective tension on the specimen. This consists of two coaxial, slotted cylinders, C_1 and C_2. The upper split grip G_1 slides into a slot in both C_1 and C_2 in such a way that it is fixed with respect to C_1 when C_2 is pushed down past it. The lower

split grip G_2 is fixed with respect to C_2 when the apparatus is assembled. The platen P_1 is also fixed with respect to C_2. Hence, the downward thrust of P_1 pushes C_2 downward in C_1, lengthening the specimen S.

EFFECT OF PRESSURE ON FRACTURE AND FLOW

Zones of "fracture" and "flow."—It has long been a geologic dogma that when a rock is deformed under a sufficiently high confining pressure it will "flow"—i.e., deform indefinitely by a process of molecular rearrangement similar to viscous flow. This conception of rock behavior has been gained from observation of the great amount of distortion in the old, highly metamorphosed rocks which have been deeply buried and subject to diastrophic forces. Further, geologists have made a sharp distinction for any one rock between the "zone of fracture" and the "zone of flow" directly dependent on the amount of confining pressure acting on a rock when it is deformed.

Experiments to date have failed to produce continuous flow. Fracture has been observed in the Solenhofen limestone under confining pressure of 10,000 atmospheres, corresponding to a depth in the earth's crust of about 22 miles. That these fractures are not a result of rapid loading is shown by experiment No. 46, in which the differential force was held constant during a large part of the plastic flow and remained constant until rupture occurred. As the confining pressure is increased, the physical character changes gradually from dominantly brittle to dominantly plastic. No sharp line can be drawn between the two.

The change in the physical character of the rocks with confining pressure is shown best by the stress-strain curves of Figures 4 and 5. The curves at low pressure (1, 2,000, and 4,000 atmospheres) are characteristic of brittle materials which break before entering the region of plastic deformation; in other words, without deviation from pure elasticity. However, the curves at high pressures (8,000 and 10,000 atmospheres) are characteristic of ductile materials which have a "yield point" on entering the region of plastic deformation, and show a "work hardening" or increase of strength before rupture takes place.

In most respects the behavior of the limestone at high pressure is

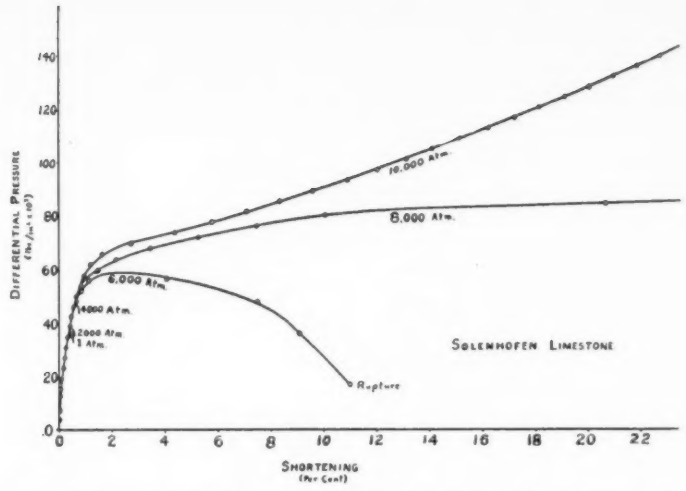


FIG. 4.—Stress-strain diagrams of Solenhofen limestone tested in compression with varying confining pressures from 1 to 10,000 atmospheres. Each curve represents one complete experiment on an individual specimen at the confining pressure which is given in atmospheres.

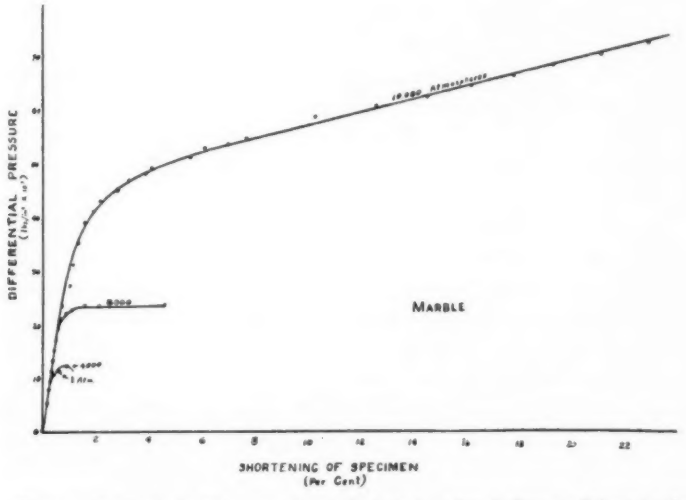


FIG. 5.—Stress-strain diagrams of marble tested under similar conditions to the limestone of Figure 4.

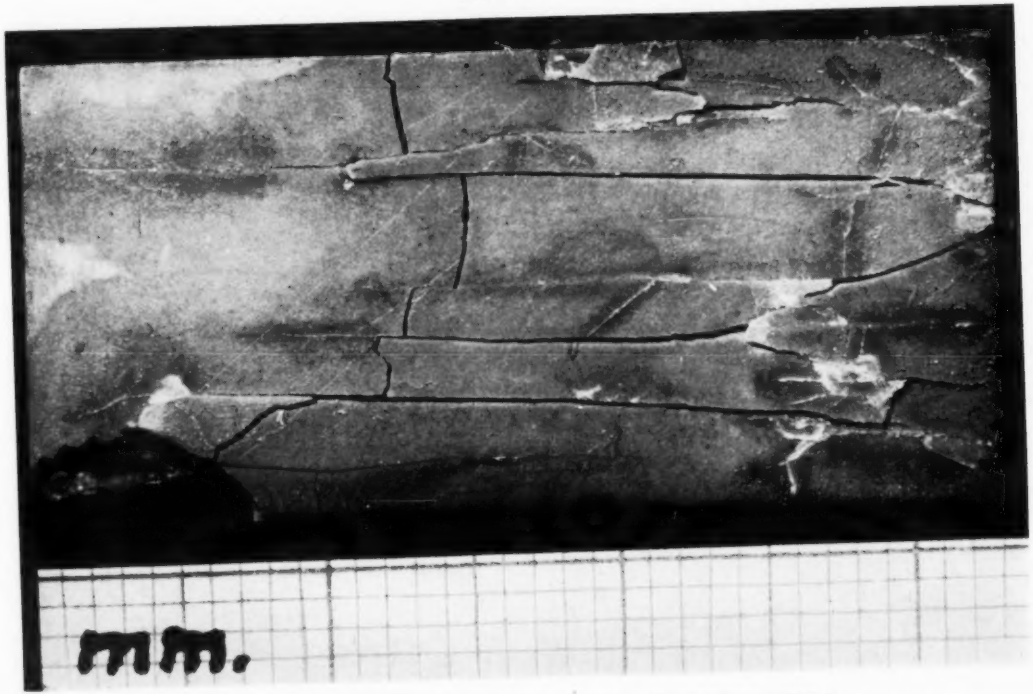
similar to that of a ductile metal at atmospheric pressure. The stress-strain curve is exactly the same. The mechanism of plastic deformation is similar to slip and twinning in the crystals. The effect of the plastic flow on the properties of the limestone is similar to the phenomenon of cold work in metals. There is even a recovery after deformation which is similar to "elastic after working" as observed in metals.

Types of fractures.—When testing materials in compression, two main types of fractures are commonly observed: "shear" fractures and "tension" fractures. The two can usually be easily distinguished. The former occur when the shear stresses exceed the strength of the crystals and hence are inclined to the direction of compression at about 45°. The surface of a shear fracture usually shows granulation and commonly is slickensided. In rocks it is generally much lighter in color than the tension-crack surfaces, owing to the fracturing and powdering of the crystals. "Tension" fractures, on the other hand, occur parallel to the direction of compression. Their surfaces are generally clean-cut fractures across the crystals with no evidence of granulation or slickensiding.

These so-called tension fractures cannot be explained by the principles of the theory of elasticity. There is no tensile force at right angles to the compression in a homogeneous medium, yet we have abundant evidence that fractures do take place exactly as though there were strong tensile forces at right angles to the direction of maximum compression.

There is a very simple hypothesis which seems to explain this type of fracture in many cases. Although it must have been obvious to many men engaged in testing materials, the writer has not seen it developed as a hypothesis before. It is this: before rupture, there is a small amount of plastic deformation accompanied by the development of Lüders' lines on the surface of the specimen. These lines seem to be the surface expression of shear surfaces within the specimen. These surfaces in a square prism occur as planes at 45° to all four faces, and distributed fairly evenly over them, with a concentration near the ends. Consequently, where any two of these surfaces intersect, a wedge is formed, with movement along the shear surfaces causing the development of tension at the point of the wedge.

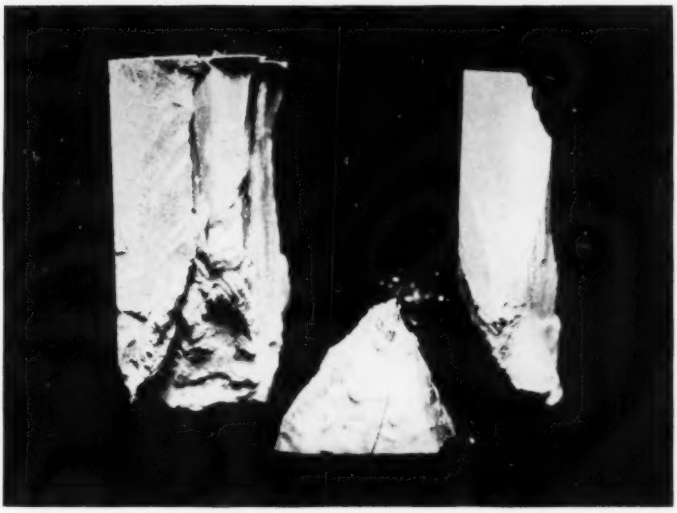
PLATE I



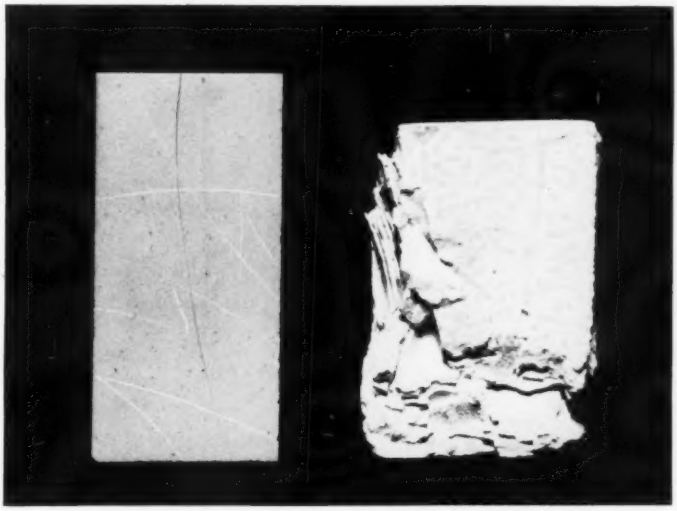
SOLENHOFEN LIMESTONE BROKEN IN LONGITUDINAL COMPRESSION UNDER A CONFINING PRESSURE OF ABOUT 100 ATMOSPHERES

(Note wedges of shear entering the longitudinal "tension" cracks)

PLATE II



A. Solenhofen Limestone Broken in Longitudinal Compression under a Confining Pressure of 4,000 Atmospheres
(Note pyramid of shear and longitudinal "tension" cracks)



B. Solenhofen Limestone Sheared, but Not Completely Ruptured under a Confining Pressure of 8,000 Atmospheres
(Specimen at left shows original dimensions)

It is in response to this force that the tension cracks develop. This relation between wedges of shear and tension cracks is shown very beautifully in Plate I. In this case every tension crack (parallel to the long axis of the specimen) is seen to have a well-developed wedge of shear entering it. Compression was applied longitudinally. The transverse cracks are believed to be due to buckling. Plate II*A* also shows the relation between shear wedge and tension fracture. This specimen is the same material (Solenhofen limestone) as the preceding figure, but broken at 4,000 atmospheres confining pressure instead of 1. This is the characteristic type of fracture found in materials slightly less brittle than the Solenhofen, such as concrete, marble, etc.

There has been some question raised as to which came first, the shear crack or the tension crack. Careful observations were made of the failure at atmospheric pressure and in every case it was observed that Lüders' lines developed first and spread slightly before rupture. This is taken as sufficient proof that the shear preceded the rupture, which takes place with explosive violence when the tension cracks open.

Professor Edgerton, of the Massachusetts Institute of Technology, very kindly co-operated with the writer in taking some high-speed moving pictures of this fracture. Exposures were taken at the rate of 720 per second with Dr. Edgerton's special camera, using an exposure time of only 1/100,000 second. However, it was found that the fracture occurred so rapidly that in one frame the specimen would be solid and uncracked and in the next it would already have separated about a quarter of an inch. It is hoped that the process may be speeded up so that it will be possible to trace the development of these fractures.

If this hypothesis as to the formation of tension cracks is correct, we would expect them to be inhibited by confining pressure. This follows directly, assuming that the liquid has no access to the point of the wedge. In this case the effective tension at the point of the wedge would be equal to the total resolved "tensile" force minus the force due to the confining pressure, so that as the confining pressure is increased, we would expect to come to a point at which no more tension cracks are formed.

Actually, there is very much less tension cracking at high values of confining pressures, but some has been observed even at 10,000 atmospheres confining pressure. Plate III*A* shows a well-developed tension crack parallel to the direction of compression. In all other cases it was restricted to a small amount of spalling off the surface. This spalling is to a large extent responsible for the irregularity of the surface of the specimen in Plate IV*A*.

This inhibition of tension cracks and the corresponding development of innumerable shear surfaces is the most striking effect of the increased confining pressure on the type of failure. In the specimens which seem to have flowed most uniformly (Pl. IV*B*) close examination shows countless shear surfaces inclined at about 45° to the direction of compression. These shear surfaces are analogous to Lüders' lines in metals, and probably bear the same relation to the plastic flow of the mass. Another example of multiple shear surfaces is shown in Plate II*B*.

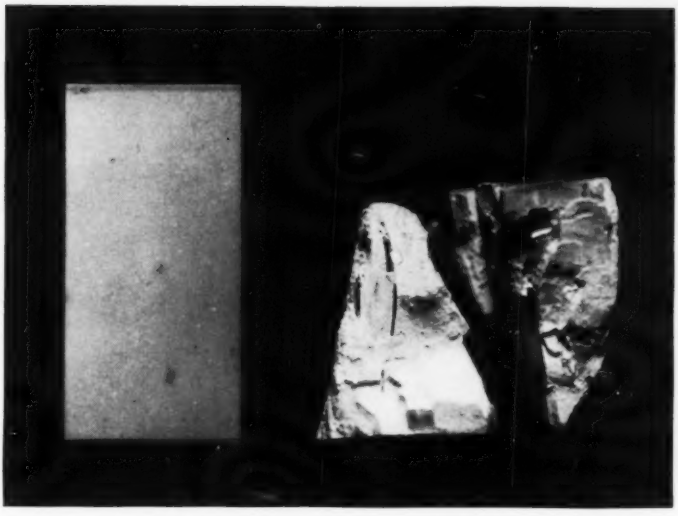
When a specimen is sectioned, these shear cracks are seen to be surface phenomena. Thus, when the specimen of Plate II*B* was sectioned parallel to the plane of the photograph, the shear cracks were observed to die out as they went inward and the whole central three-quarters of the specimen was homogeneous as seen under the microscope. I think there is no doubt that the shearing continues through the center of the specimen. The difference is that at the center, where confined on all sides, the shear surfaces never become separated beyond the limit of molecular cohesion, and consequently leave no visible effect.

This seems to indicate that at high pressure failure in the ordinary sense is a near-surface phenomenon. It raises again the question as to whether all faults originate at the surface of the earth and are propagated downward.

Angles of surfaces of shear.—It has been stated repeatedly that the angles of the planes of shear failure change markedly with increasing confining pressure. Kármán observed an increase from 27° to 38° 30″ (angle between the plane and the direction of maximum compression), with an increase in confining pressure from 1 to 685 atmospheres.[7] It is extremely difficult to get accurate measurements on

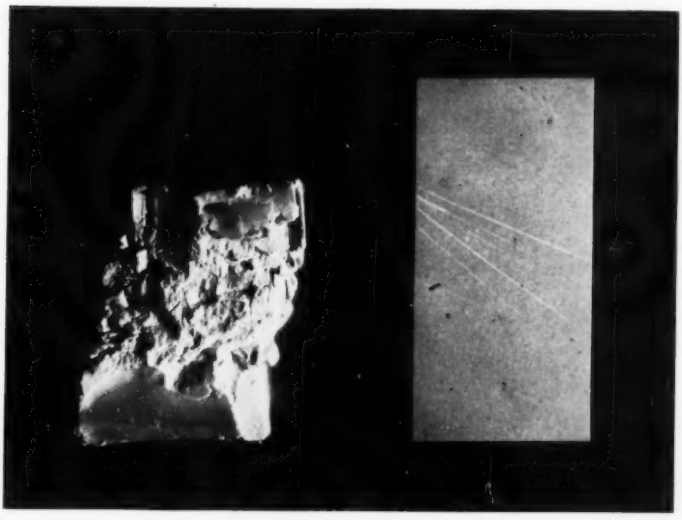
[7] Th. von Kármán, "Festigkeitversuche unter allseitigem Druck," *Zeitschr. des Ver-*

PLATE III



A. Solenhofen Limestone Fractured under 9,850-Atmosphere Confining Pressure after Undergoing 23 Per Cent Shortening by Plastic Deformation

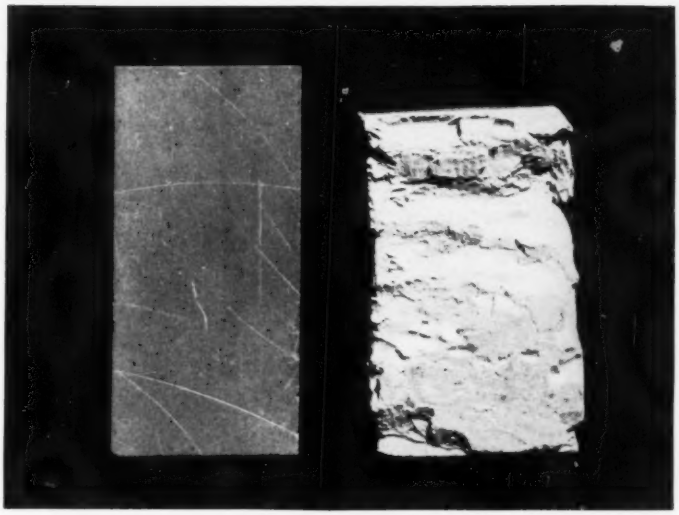
(Duration of run 21 hours; note vertical "tension" crack and high-angle shear surfaces)



B. Solenhofen Limestone Ruptured under 9,400-Atmosphere Confining Pressure after Undergoing 28.5 Per Cent Plastic Deformation

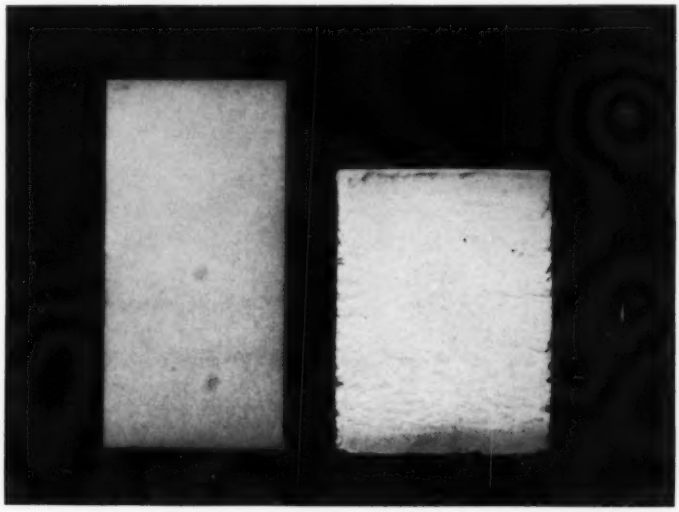
(Duration of run 1.5 hours; although its strength dropped almost to zero, the limestone was still coherent when removed from the apparatus)

PLATE IV



A. Solenhofen Limestone Deformed Plastically under 9,700-Atmosphere Confining Pressure

(Note flaking)



B. Solenhofen Limestone Plastically Deformed 30.3 Per Cent under 10,000-Atmosphere Confining Pressure

(This specimen was supporting a differential pressure of 185,000 lb. per square inch)

the angles of the planes of shear. This can be readily seen by study of photographs showing rupture (e.g., Pls. I, II*B*, and III*A*, in the present paper).

A complicating factor in the determination of the angles of the planes of shear is the common integration of minute shear and tension fractures to produce a surface whose angle varies from the characteristic angle of the shear surface (nearly 45° to the direction of compression) to that of the tension fracture (parallel to the direction of compression). Sometimes when these surfaces are examined in detail it is possible to distinguish the two types of fractures; occasionally it is possible to get measurements on each one.

Now in some cases this close but often unobservable relation between shear and tension fractures may lead to an erroneous measurement of the angle of shear. Since there is a tendency for tension cracks to be inhibited by the action of confining pressures, of course pressure has a great effect on the angle of this hybrid fracture. In lessening the tension cracks it greatly increases the angle of the surface produced. It may be that this effect has in some cases been mistaken for a true effect on the angle of shear.

The angles of the surfaces of shear as observed in the writer's experiments are not regular enough to warrant quantitative measurements, as can be seen from the photographs reproduced in this paper. However, two general observations may be made: (1) the shear surfaces on which rupture occurs are always inclined to the direction of compression at angles less than 45°; (2) fractures at the highest confining pressures (8,000–10,000 atmospheres) have shear surfaces inclined to the direction of compression at low angles as shown in Plates II*B* and III*A*.

The flow observed in these experiments (amounting to a shortening of 35 per cent in one case) probably is not the same type of flow that occurs in the depths of the earth. Thin sections indicate that the flow is entirely due to slip and twinning in the crystals. In metamorphic rocks, on the other hand, much of the deformation must have been accomplished by recrystallization. The school of Sander

eins deutscher Ingenieure, Vol. LV (1911), 1749–57. For a discussion of this paper see W. H. Bucher, "The Mechanical Interpretation of Joints," *Jour. Geol.*, Vol. XXIX (1921), p. 13.

leans strongly toward belief in a mechanical flow which is very similar to the flow in these experiments. However, marble is seldom twinned so completely as in some of my specimens (see, e.g., Pl. V*C*).

The reasons for this difference in type of flow are not established definitely, but it may be that the root of the difference is the fact that no solvents have access to the specimens and deformation is done at low instead of high temperature. Both conditions may perhaps be attained in the laboratory with enough patience and ingenuity. Another factor cannot be dealt with so easily—geologic time. There is no evidence from experimental work on rate of deformation or from theory that time alone will have any effect on the nature of the deformation so far as purely mechanical deformation is considered. It must, however, have a great effect on flow by recrystallization. In this case time is, without doubt, as important as any other factor.

Because of the great difference between the type of flow produced in the laboratory and that in nature, I question the value of determining the depth of the zone of flow by present experimental methods. However, it may be said that the present experiments would indicate that F. D. Adams' figures on the depth of the zone of flow are too low.[8] It may be that better accord with Adams' results will be reached when more experiments are performed with a confining jacket to keep the liquid out of the pore spaces (an effect which will be discussed later). In any event, it is impossible to predict the depth of the zone of flow until the effect of temperature on the characteristics of rocks at high pressure is determined.

One fact of importance came from the comparison between the Solenhofen limestone and the marble. The former is a compact, very brittle rock of great strength (36,500 lb. per square inch). The latter is a weak, loosely compacted rock with a crushing strength of only 11,700 pounds per square inch. According to prevalent geological theory, it should follow that the weak rock will flow at a much lower value of confining pressure than the strong Solenhofen.

This is not the case. Eight thousand atmospheres is approxi-

[8] "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *loc. cit.*

mately the lower limit of flow for both (lower limit of flow taken arbitrarily as the point at which the rock can be deformed plastically 5 per cent without rupturing). At this pressure it seems that the Solenhofen limestone will even flow a little more than the marble. Thus, the amount of confining pressure necessary to cause flow instead of brittle fracture appears to depend on the character of the individual crystals composing the rock rather than on its strength.

STRENGTH OF ROCKS UNDER HIGH PRESSURE

"Strength" is a misleadingly simple term. To the average person it seems easily defined as the amount of force which a body will withstand without fracturing. It became apparent to geologists many years ago that the definition is not so simple, but involves a time factor—that is to say, some materials will withstand high stresses for a short time, but will rupture or deform in response to smaller stresses which are active for a longer time.

Since most rocks at atmospheric pressure are brittle and little plastic deformation occurs before rupture, strength of such rocks is simply and easily measured and is found to be independent of time, at least to the limit of sensitivity of our measurements. Rocks under high pressure present quite a different problem.

In measuring the strength of rocks under high confining pressures we are confronted with the problem of choosing the point on the stress-strain curve (Fig. 4) that corresponds to the significant value for geological purposes. Two points are evident: (1) the elastic limit, or the limit of proportionality of the curve; (2) the ultimate strength, or the maximum stress supported by the rock before rupture occurs.

Ultimate strength is here used as the mechanical engineers define the term. The adjective "ultimate" was applied by them to distinguish the final strength at the rupture point from the strength at the "yield point." This usage is misleading because the ultimate strength is found to vary with the confining pressure and the duration of the test.

The "elastic limit" is changed only slightly by applying a confining pressure to the specimen. Thus, a confining pressure of 10,000 atmospheres raises the elastic limit of the Solenhofen limestone

about 10 per cent. The ultimate strength, however, is very greatly changed by the confining pressure, as is shown in Figure 6. A pressure of 10,000 atmospheres increases the ultimate compressive strength more than 600 per cent.

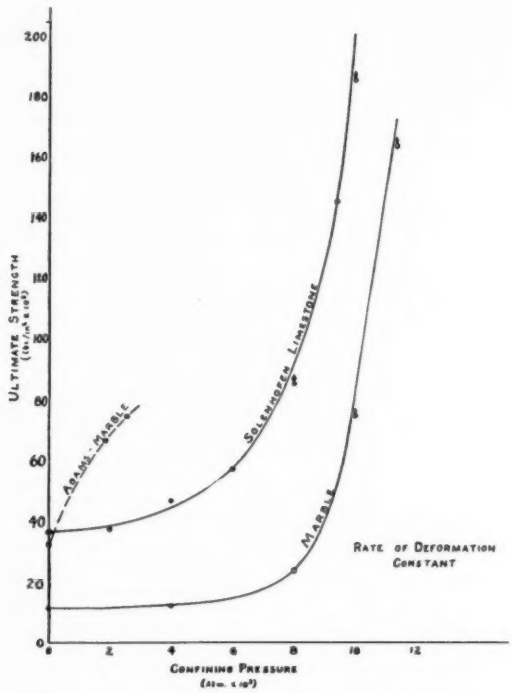


FIG. 6.—Ultimate strength as a function of confining pressure. Each point represents the maximum differential pressure supported by a specimen tested at the appropriate value of confining pressure.

F. D. Adams' measurements gave an entirely different relation between strength and confining pressure as shown in Figure 6.[9] This is not hard to understand in view of the fact that Adams' specimens were prevented from fracturing by the confining steel jacket, and also because he was not able to measure accurately the confining pressure.

[9] Adams and Bancroft, *op. cit.*, p. 636.

Since this work was done Dr. P. W. Bridgman has developed an entirely different technique of measurement which permits him to measure the "plastic flow point" under shear stress as a function of confining pressure.[10] He has been so kind as to make a series of

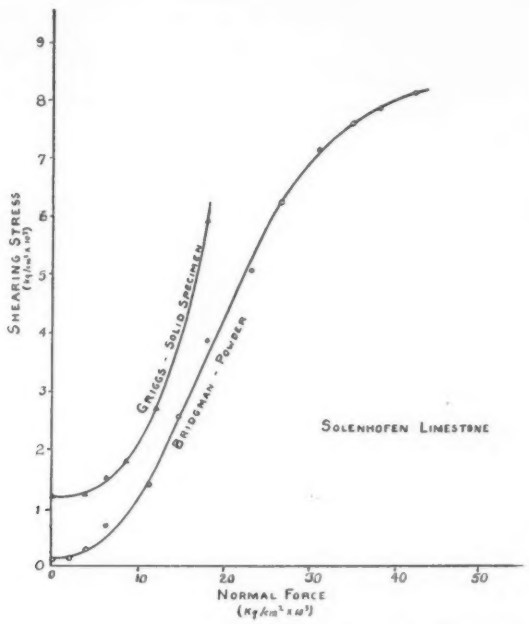


FIG. 7.—Comparison of my determinations of ultimate strength as a function of confining pressure with Bridgman's measurement of the "plastic flow point."

measurements of this type on the Solenhofen limestone, and to let me reproduce his results in Figure 7. His specimens consist of powder, so one would expect the strength to be less than that of a crystalline aggregate. When my measurements are recalculated to the same co-ordinates that Bridgman uses, the two compare as shown in Figure 7. It is interesting that these two types of measurements, differing so greatly in method, should give results so nearly alike.

[10] P. W. Bridgman, "Effects of High Shearing Stress Combined with High Hydrostatic Pressure," *Phys. Rev.*, Vol. XLVIII (1935), 825–47.

Effect of time on strength.—Below the elastic limit it appears that the rock will not fail, no matter how long the force be applied. Also, no permanent set occurs, within the limits of sensitivity of the present measurements. Hence we see that the elastic limit of a rock is a constant, independent of the time of application of the force. Ultimate strength, on the other hand, is found to vary notably with the duration of the deforming force. Figure 8 shows approximately the nature of the relation between ultimate strength and time. This

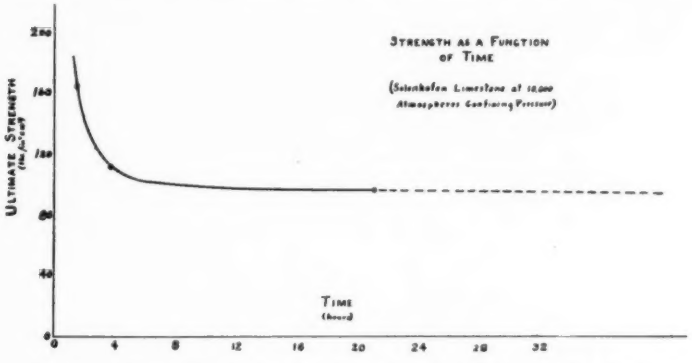


Fig. 8.—Ultimate strength plotted as a function of the duration of the test (10,000-atmosphere confining pressure). Each point represents the ultimate strength of one specimen with the duration of its test run until rupture occurred.

time-strength curve is of such a nature as to suggest that it is asymptotic to a certain value of strength at infinite time, which means simply that, if any force below this limiting value is applied to the rock for any finite time, the rock will not fail. There are not yet enough data to give more than a rough suggestion that this might be true. It is to be hoped that future work will establish the time-strength relation so that it may be extrapolated.

Figure 9 shows the nature of the plastic yield near this value of strength. This is a curve of the Solenhofen limestone under a confining pressure of 10,000 atmospheres, equivalent to that 22 miles deep in the earth's crust. The limestone was subjected to a differential force increasing to a certain value, then held constant while the plastic deformation was observed as a function of time. Then the

force was increased to a higher value and the process repeated. At low values of the force no plastic deformation took place, regardless of time. For higher values it was found that the rate of plastic deformation varied in proportion to the applied force, as is shown on this curve. Each of the horizontal parts of the curve represents an interval during which time the compressive force was maintained constant.

It is interesting to examine the relation between strain and time for these parts of the curve where the differential force is kept con-

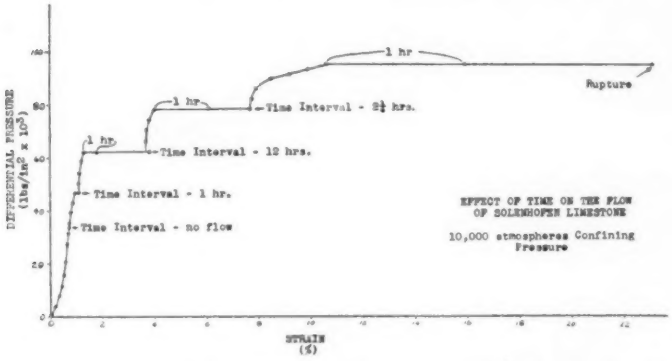


FIG. 9.—Stress-strain diagrams of one experiment on Solenhofen limestone to show the effect of time. At each point where the curve is horizontal, the stress was maintained constant for the interval shown.

stant. Figure 10 is plotted from the same experiment as Figure 9, each curve of Figure 10 corresponding to a flat part on the curve of Figure 9. These strain-time curves are exactly similar to the "creep" of metals at high temperature. This relation between deformation and time is characteristic of the plastic flow of crystalline aggregates. It is what Michelson has termed "elastico-viscous flow."[11]

In order to understand more fully the implication of this "creep," it is necessary to consider one other experimental fact—one which was not anticipated. It was expected that a rock would be more ductile (i.e., would deform more without breaking) when deformed

[11] A. A. Michelson, "Laws of Elastico-Viscous Flow," *Jour. Geol.*, Vol. XXV (1917), pp. 405–10; *ibid.*, Vol. XXVIII (1920), pp. 18–24.

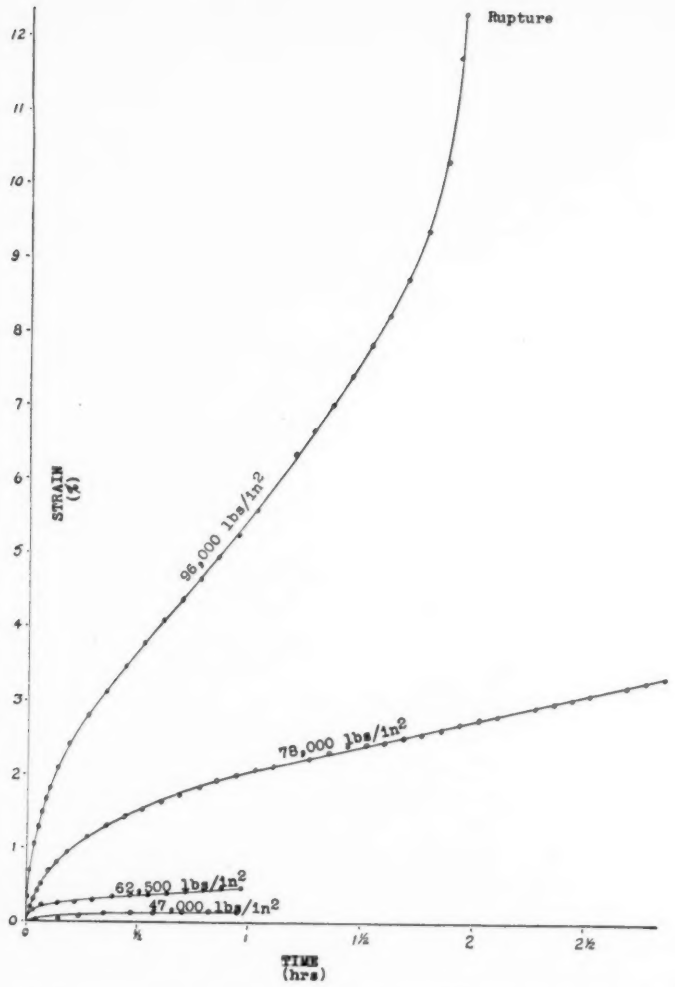


FIG. 10.—Data from the experiment of Figure 9 plotted to show the relation between strain and time at each point where the stress was held constant.

slowly than when deformed rapidly. A quotation from a recent paper shows well the common opinion of geologists on this subject:

> The manner of yield, by fracture or by rock flow, is influenced by the rate of application of stress. In the depth range of deep earthquakes, where high temperatures and containing pressures favor failure by rock flow, fracture results when differential stress is applied too rapidly to permit flow.[12]

Just the opposite effect was found experimentally. Figure 11 shows the amount of plastic deformation before rupture in a series

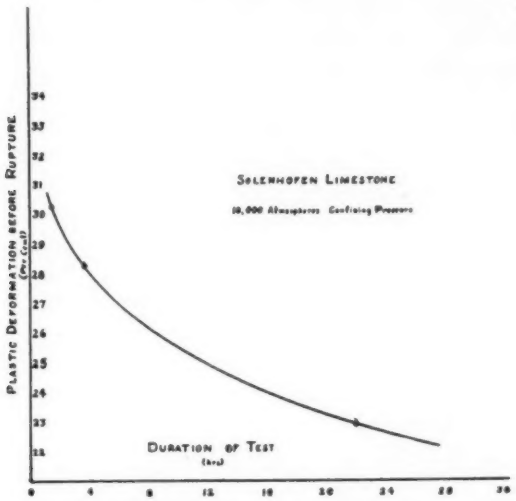


Fig. 11.—Data of Figure 8 plotted so as to show the relation between plastic deformation before rupture (ductility) and the duration of the test.

of similar specimens, compressed to the point of failure under similar conditions of temperature and confining pressure, but with different rates of increase of differential pressure. Here it is seen that the longer the duration of the experiment, the less the amount of plastic yield before rupture. These tests are the same three which furnished the data for the curve of Figure 8.

[12] Andrew Leith and J. A. Sharpe, "Deep Focus Earthquakes and the Strength of the Earth," *Preliminary List of Titles and Abstracts of 48th Annual Meeting, Geol. Soc. Amer.* (1935), p. 48.

This means, then, that if plastic deformation occurs continuously and at a rate which does not approach zero at infinite time, sooner or later the specimen will fail, no matter how slow that plastic flow is. Hence, *at the value of strength which holds for infinite time, there must be no finite continuous plastic deformation. Also, no sudden application of high stress is necessary to produce fracture.*

Returning to the creep curves of Figure 10, we see the method of measuring the strength for infinite time. The curves seem to flatten out after their first sharp uprise, and become linear. If this straight-line relation can be shown to be true over long periods of time, then it is necessary only to find the maximum differential force under which the linear part of the curve is a horizontal line—in other words, deformation does not increase with time. It follows that this is the strength for infinite time from the principle enunciated in the preceding paragraph. Practically, the measurement of this strength is not so simple, because of the limits of sensitivity of strain measurement and the limited amount of time which a laboratory experiment may consume.

Is it not this value of strength which is of interest in geology, since the important thing is the fundamental fact that the crust supports a finite load for geological ages, and the amount of deformation which may occur is immaterial, so long as that deformation is not continuous, but ceases before the rock has been greatly deformed?

To fit this special usage of the word "strength," the term "fundamental strength" is proposed. It may be hypothetically defined as follows: the "fundamental strength" of a body is the differential pressure which that body is able to withstand under given conditions of temperature and confining pressure without rupturing or deforming continuously. (Ultimate strength would be a more satisfactory term, but it is ruled out because of its common usage in laboratory testing to designate an entirely different property.)

This experimental work would seem to give a possible clue to the cause of deep-focus earthquakes. If the rocks at great depths are crystalline and follow these principles, it is not necessary to have sudden increase of stress to cause fracture, but merely long-continued stress above the fundamental strength will suffice.

ELASTIC AFTER-WORKING

Among the many similarities between the behavior of the limestone at high pressures and the behavior of metals is the phenomenon of a gradual return after the differential force is removed. A specimen may be observed to grow longer after removal from the apparatus. There are indications that this is far greater than in the case of metals, but the difficulties in measuring it immediately after the differential pressure is released make it impossible to answer this completely with the present technique.

Measurements of this effect are limited to one experiment. In this case the specimen was deformed 30 per cent but not ruptured. On removing it from the apparatus it appeared to have flowed uniformly (Pl. IV*B*). Its length was measured as soon as possible, but this was about an hour after the differential pressure was released, owing to the necessity of decreasing the hydrostatic pressure slowly, and the time consumed in taking the apparatus apart. Subsequent measurements of its length were as shown in Table I.

TABLE I

Time after Differential Pressure Release (Hours)	Length (Inch)
1	0.7726
16	.7752
20	.7756
40	.7757
One week	0.7759

There are various explanations of this afterworking return. Joffé has adduced good evidence to indicate that, in halite, this effect is a result of gradual dissipation of charges resulting from the piezoelectric effect caused by the strain.[13] It is difficult, however, to see how this explanation would apply to metals because of their high conductivity.

Whatever its cause, it is of great interest to geologists since it indicates a much greater "elastic return" than was formerly thought

[13] A. F. Joffé, "The Physics of Crystals," McGraw-Hill Book Co., New York, 1928, pp. 23–31.

possible by calculations from elastic theory. In one case, after deformation at a confining pressure of 10,000 atmospheres, the "elastic return" was six times as great as calculated from the elastic modulus. The present apparatus is not adapted to accurate measurements of this effect under high pressure.

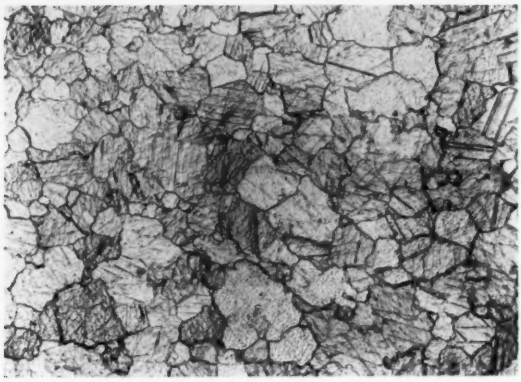
THE EFFECT OF JACKETING THE SPECIMEN

In the experiments described so far, the specimen had been uncovered, so that the liquid under high pressure has had access to the pores of the rock. There is much evidence which indicates that rocks at depth are not saturated with water.[14] In order to duplicate these conditions, it is necessary to devise some sort of a jacket for the specimen which will transmit the confining pressure of the liquid to the specimen and yet will not permit the liquid to enter its pores. In this experimental work the extreme case was taken in which no liquid was present in the pores of the rock.

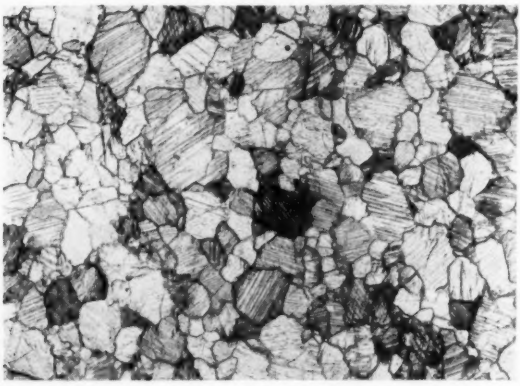
A jacket such as that just mentioned presents difficulties to the experimenter. It must yield with the specimen, offering no resistance to deformation, and yet be sufficiently strong and impermeable to keep the liquid out of the pores. Several materials were tried before one was found which met these conditions. Rubber was tried first, but it was impossible to make leakproof contacts with the steel plates at the ends which transmit the pressure to the specimen. Collodion was tried, but without success, since it was permeable to the liquid at high pressure. Lead foil was tried without success, though it is possible that a more expert manipulator could make it work. Copper foil was tried on square prisms with indifferent success. The foil was leakproof for small amounts of deformation, but split along the corners when the deformation exceeded a small percentage. This led to the use of drawn copper tube, which was made to fit half-inch cylinders. This tube was specially drawn, with a wall thickness of 0.010 inch. It was an exact fit for the specimens, and, after annealing, was soldered to the steel end plates. This form of jacket was found to be easy to apply and to be tight under deformations up to

[14] W. Lindgren, *Mineral Deposits* (New York: McGraw-Hill Book Co., 1933), pp. 34–40.

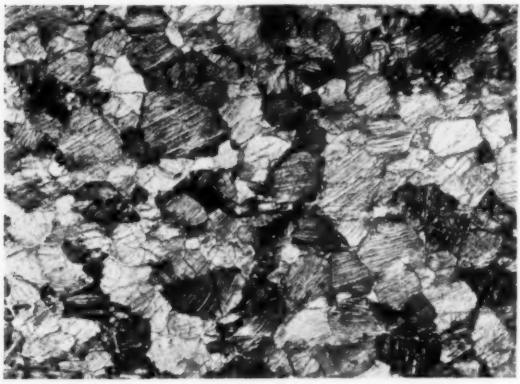
PLATE V



A. Photomicrograph of Thin Section of Undeformed Marble
(Uncrossed nicols; magnification 20×)



B. Marble Plastically Shortened 4 Per Cent under 8,000-Atmosphere Confining Pressure
(Uncrossed nicols; 20×)



C. Marble Plastically Shortened 24 Per Cent under 10,000-Atmosphere Confining Pressure
(Uncrossed nicols; 20×)

25 per cent, with no evidence of splitting at this value. Up to date no experiments have been carried to rupture with this jacket on.

Only two experiments have been performed with this type of jacket. The deformation is the most uniform that has yet been obtained—apparently the most perfect plastic flow. These experiments indicate that the strength under high confining pressure is much greater when the specimen is jacketed than when the liquid is free to enter the pores. The strength of the Solenhofen limestone under 10,000 atmospheres confining pressure was thus increased 40 per cent—from 160,000 to 225,500 pounds per square inch. At 8,000 atmospheres the strength of the marble was increased 28 per cent. The jacket itself has very little strength (less than 20 lb. will crush it), so that this introduces no source of error in the strength measurements.

It is planned to make a complete series of experiments with the specimens jacketed in order to measure the effect on all the properties.

EFFECT OF DEFORMATION ON ROCK FABRIC

In studying the mechanism of plastic deformation it is most important to observe how each individual crystal reacts to the deforming force. For this purpose the specimens were sectioned and studied with the microscope. It was impossible to detect any change in the Solenhofen limestone, because it is too fine grained to be resolved even under oil-immersion lenses. The marble used in these experiments was ideally suited for this work, consisting of fairly pure calcite with a grain size of about 0.35 mm. A specimen of the original marble was sectioned for comparison. The specimens and sections were so cut that they all had the same orientation with respect to the block from which they came.

This sectioning after deformation was practical only in those cases where the marble "flowed" (i.e., deformed without losing cohesion). At present two specimens have been studied — one deformed under a confining pressure of 8,000 atmospheres and one at 10,000 atmospheres. In both of these specimens deformation seems to be purely plastic, with no evidence of cataclasis. However, the specimen at 8,000 was shortened only 4 per cent, whereas the one at 10,000 at-

mospheres was shortened 24 per cent. Plate V is a series of photomicrographs showing the texture of these two specimens as compared with the original marble.

Two things are at once apparent: (1) there is no marked change in grain size or shape; (2) the crystals of the deformed marble are very highly twinned, whereas the original marble is only slightly twinned. Further, there is an apparent orientation of the traces of the twin planes as seen in the section.

To study this orientation of twin planes, Sander's method of rock fabric analysis was employed.[15] This consists in determining the orientation of the twin planes with respect to the plane of the specimen and the direction of compression. Their positions are plotted as poles of the normals to the twin planes on a Schmidt equal area stereographic projection. The result is contoured in the usual manner and shown in Figures 12 and 13. The rock fabric is seen to have been remarkably changed by this 24 per cent artificial shortening.

This diagrammatic representation of the distribution of the twin planes shows a very high degree of orientation, contrasted to the lack of orientation in the undeformed marble. Because of the very great development of twinning, the original twinning is almost completely obliterated, or is so inconspicuous that it escapes notice in the deformed marble.

This diagram is very useful in determining the relation of the position of the twin planes to the direction of the compressive force. Here, for almost the first time, we have the development of twinning by a force which is known with a high degree of accuracy both in direction and in magnitude. The twin planes are inclined to the direction of compression at all angles, but with a very pronounced maximum between 65° and 70°. This is very interesting, since the direction of maximum shear stress is at 45° to the direction of compression, and the metallurgists have shown that twinning develops on those twin planes of the crystal which are so oriented that they have the maximum resolved shear stress.

[15] Bruno Sander, *Gefugekunde der Gesteine* (Vienna: Julius Springer, 1930); E. B. Knopf, "Petrotectonics," *Amer. Jour. Sci.*, Vol. XXV (1933), 433–70; James Gilluly, "Mineral Orientation in Some Rocks of the Shuswap Terrane as a Clue to Their Metamorphism," *ibid.*, Vol. XXVIII (1934), 182–201.

This incomplete study is here presented merely to give an idea of the qualitative effect of artificial deformation on rock fabric, and to give a hint of the possibilities of the experimental method. Since the interpretation of petrofabric analyses at the present time is somewhat uncertain, it is hoped that some guiding principles can be

FIG. 12

FIG. 13

FIG. 12.—Petrofabric diagram of marble before deformation. Plot of 200 poles to twin planes. *C–C* axis is the long axis of the specimen. Twin planes not measured in the central circle because of the limitations of the universal stage.

FIG. 13.—Petrofabric diagram of marble after 24 per cent deformation under confining pressure of 10,000 atmospheres. Plot of 200 poles to twin planes. *C–C* axis is the direction of compression (long axis of the specimen).

In both figures the shading has the following significance:

- ☐ 0–2 per cent of points per 1 per cent of area
- ▨ 2–4 per cent of points per 1 per cent of area
- ☐ 4–6 per cent of points per 1 per cent of area
- ■ greater than 6 per cent of points per 1 per cent of area

worked out by experimental deformation. Dr. Eleanora B. Knopf is undertaking, with the writer's co-operation, a detailed study of the effect of artificial deformation on rock fabric as one of the projects of the National Research Council Committee on Structural Petrology.

DEFORMATION OF QUARTZ UNDER HIGH PRESSURE

It was expected that if high-enough confining pressure could be attained, quartz could be made to deform plastically. Four experiments were performed, all at room temperature, one at 10,000 atmospheres, and three at 12,000 atmospheres confining pressure. The first three specimens were cylinders parallel to the *c*-axis—cut from single crystals. There is no evidence of plastic deformation in any of these. Further, the strength of the quartz is increased considerably above its strength at atmospheric pressure, so that to deform it at higher pressures, an enormous differential force will be needed.

In the first experiment, at 10,000 atmospheres, a differential pressure of 131,000 pounds per square inch was applied with very little effect. One striking development in this experiment was the formation of cleavage cracks, poorly developed, but definitely in planes parallel to the *c*-axis and inclined to each other at about 60°. Prismatic cleavage of quartz is fairly common, but so far as known it has not previously been produced experimentally.

In the second experiment, at 12,000 atmospheres, a differential force of 437,000 pounds per square inch was applied to the specimen. According to the extensometer, it seemed to be flowing plastically, so the pressure was released and the specimen examined. The quartz was clear and undeformed. It had, however, been pushed down into the chrome-molybdenum steel plate on which it rested, which it penetrated to a depth of about 1 mm.

In the third experiment, also at 12,000 atmospheres, a differential pressure of 487,000 pounds per square inch was attained. At this point the specimen broke with a violent explosion. The stress-strain curve shows that deformation up to the point of rupture was purely elastic. The fracture was a combination of shear and conchoidal fracture. The shear surfaces are very well developed. They have an angle obtuse toward the direction of compression—the only time this has been observed, and possibly because the rhomb angle is obtuse to the *c*-axis.

In these three experiments shearing stress was high on the rhombohedral planes of the crystals, but zero on the prism planes. Since there is evidence that quartz slips on prismatic planes (see Sander), in the fourth experiment the cylinder was cut with its axis inclined at

45° to the *c*-axis of the crystal. Results were similar to the third run, except that the strength was lower—425,000 pounds per square inch, and some rhombohedral cleavage developed parallel to the direction of compression. Fracture occurred along a well developed shear surface as in the third experiment.

The shear surfaces were coated with a shiny black substance, highly slickensided. It is thought possible that this is elemental silicon, liberated by the enormous shearing stress at rupture. Dr. A. B. Greninger attempted to identify it by x-ray analysis, but found that it was too finely crystalline (probably colloidal) to produce an x-ray pattern. He also investigated the material immediately adjacent to the shear surface and found it to give the characteristic lines of alpha crystoballite. Farther away from the shear plane quartz appeared, but here it was finely pulverulent, with a grain size of about one-tenth of a micron.

These experiments show that at pressures up to 12,000 atmospheres, corresponding to a depth of 25 miles in the earth's crust, quartz has no tendency to flow at room temperature. Here, again, the factors of temperature and time are of great importance, but they have not as yet been evaluated, and it is impossible to predict their effects quantitatively.

TENSILE TESTS UNDER HIGH CONFINING PRESSURES

All experiments described herein thus far have dealt with compressive tests in which the longitudinal stress is high and the lateral stresses equal and low. It seemed that tests in which the reverse is true—where the longitudinal stress was low and the lateral stresses high—might yield information of value in testing existing theories of rupture. Consequently, an apparatus was devised to attain this end, as described in the section dealing with apparatus.

Dr. P. W. Bridgman performed a series of experiments with a somewhat similar stress distribution to measure what he called the "pinching-off effect."[16] In these experiments a rod of the material to be tested was placed in a short cylinder with stuffing boxes at each end so that the rod projected through both stuffing boxes. When the pressure inside the cylinder was increased (liquid pressure), the spec-

[16] *The Physics of High Pressure*, pp. 91–93.

imen was broken and the ends expelled violently through the stuffing boxes. The only disadvantage of this method is that the hydrostatic pressure under which failure may be investigated is not variable, but is a constant fixed by the strength of the material being tested. To the best of the writer's knowledge, the present apparatus is the only one which has yet been used for the measurement of tension tests under all values of confining pressures.

It is very difficult to get an accurate measurement of the tensile strength of a rock at atmospheric pressure because it is so extremely brittle. A plastic material will yield so as to equalize any irregularities in the grips and prevent great unevenness of pressure, but a brittle material will not. Consequently, it is very difficult to avoid breakage at the grips. It is necessary to neck the specimen down considerably before it will break in the middle rather than in the grips.

Presumably, since the limestone becomes more plastic under high pressure as shown in the compression tests, a similar change in properties should be observed in tension tests. Hence the writer reasoned that these difficulties of tension-testing at atmospheric pressures would disappear in tests at high pressure.

Completely reversing the predictions, the limestone at a confining pressure of 10,000 atmospheres behaved as a brittle substance. No plastic deformation could be measured before rupture. Also, the fracture was of exactly the same nature as at atmospheric pressure—a typical brittle fracture, which geologists would describe as a tension break.

This experiment was taken to indicate that the critical value of pressure necessary to cause flow was not the confining pressure, but rather the value of the maximum principal force at the rupture point—the confining pressure plus the differential pressure. In compression of the Solenhofen, flow is prominent at 8,000 atmospheres, and at this confining pressure the differential pressure to cause much flow is 4,500 atmospheres. Thus, the maximum pressure is 12,500 atmospheres. From this it was thought that if a specimen were surrounded by a pressure of 13,000 atmospheres and then tested in tension, it would behave plastically.

A second experiment was therefore performed in which the con-

fining pressure was 13,200 atmospheres. However, the results were not at all in accord with the hypothesis just outlined. The specimen still showed no evidence of plastic flow. Again the break was a typical brittle "tension break" of exactly the same character as in the previous experiments.

The paradox of these tension tests has been shown by Bridgman in his treatment of the "pinching-off effect."[17] Since the tensile strength is very low compared to the confining pressure, when rupture takes place there is not a tensile force acting on the specimen but actually a very large compressive force equal in magnitude to the difference between the confining pressure and the tensile strength. Although I have repeatedly called this difference in force a "tension," one immediately sees that actually at the moment of rupture there is a large compressive force acting across the plane on which rupture takes place, if Bridgman's reasoning is accepted.

Two hypotheses are advanced to explain this effect. Bridgman has suggested that the stability relations of the atoms in the crystals are so altered by the application of hydrostatic pressure that in order to cause loss of cohesion and consequent rupture it is necessary to separate them a smaller amount than when no external pressure is applied—that the governing factor is differential force, not absolute force.

The second hypothesis is that rupture is due to the liquid pressure directly. In all these tests the liquid is free to enter the pores of the specimen. Now when the longitudinal force is decreased by the "tension" apparatus, it is conceivable that the liquid in the surface cracks and pores exerts so much pressure that rupture occurs. The effect on the specimen is just as though a liquid under a pressure equal to the differential pressure were surrounding the specimen but not the ends. In this case it is easy to see how it might enter microscopic surface cracks and act as a wedge, splitting the rock on planes parallel to the ends.

This last hypothesis is important to consider before applying the results of these tension tests to geologic conditions. If it is operative, then these experimental results have no value in determining the actual tensile strength of the rock under high pressure or the brittle

[17] *Ibid.*, p. 91.

nature of it. Neither do they have any application in geology, since it is highly improbable that conditions ever exist in nature where the pressure on a liquid surrounding a rock is higher than the pressure due to the weight of the overlying rocks (at depth), with the exception of forcibly injected magmatic fluids. Unfortunately, no way has been devised to jacket the specimens in tension tests so that the liquid cannot enter the pores. It seems unwise to consider the geologic implications of the fact that the limestone appears to be just as brittle under high pressure as at low—truly confounding implications!

FIG. 14.—Solenhofen limestone broken in torsion under 10,000-atmosphere confining pressure.

TORSION TESTS UNDER HIGH PRESSURE

Since torsion tests have less tendency to produce tension fractures than do compression tests, and more tendency to produce shear fractures than do tension tests, it was expected that the behavior of materials in torsion at high pressure would be between the two extremes which have been described. It was expected that the yield would be more plastic than the tensile tests showed, and less plastic than in the compression tests. However, since no experiments in torsion have ever been made under conditions of high confining pressure, these expectations were not to be trusted.

In the one experiment that has been performed with the present apparatus—on Solenhofen limestone under 10,000 atmospheres con-

fining pressure—the effect did not agree with the predictions. The limestone failed in the manner characteristic of brittle materials subject to torsion, as is shown in Figure 14.

At the present time no explanation of this brittle behavior is known. It is extremely important for geologists to know the reason for this anomalous fracturing in tension and torsion before speculating about the deformation of rocks deep in the earth's crust. It is to be hoped that an explanation will soon be forthcoming.

PLANS FOR FUTURE WORK

The present preliminary report does little more than outline the field of this type of high-pressure investigation. It is to be hoped that other laboratories will become sufficiently interested in this work to undertake some phase of it.

The plans of the writer are to continue the investigations with particular emphasis on the following points:

1. Investigation of the effects of temperature on strength, rate of flow, fracture, nature of the plastic deformation.

2. Effect of mineralizers for a few simple cases to see if high temperature and high pressure make possible recrystallization which cannot be produced otherwise. Also, to investigate their effect on strength—particularly of quartz.

3. Effect of time—proceeding with the experimentation as outlined in this paper.

4. Study of the effects on rock fabric—in co-operation with Dr. Eleanora B. Knopf.

5. Carry the strength measurements to higher values of confining pressures. It seems feasible to extend the range up to 20,000 atmospheres.

6. Extend the studies to various other types of rocks and minerals.

It is easy to state in a few sentences plans that take years of work to consummate. Consequently, it is futile to discuss all the other ideas which clamor for attention. The foregoing list will last a good five years if worked out completely.

CONCLUSION

This paper presents the first results of a program of research on the deformation of rocks under high confining pressures. Their ap-

plication to geology is not immediate, but must wait in most cases until all the parameters, such as time and temperature, have been evaluated.

An apparatus has been devised for the investigation of rock deformation at high pressures which is free from the three major defects of F. D. Adams' apparatus. It permits the accurate control of confining pressure throughout the experiment, the accurate measurement of differential pressure on the specimen, and free fracturing in the specimen. Further, the range of confining pressure is extended from Adams' 3,000 atmospheres to 13,000 atmospheres, or the equivalent of about 28 miles deep in the earth's crust. However, the confining pressure is supplied by a liquid—and hence is not directly similar to geologic conditions.

Strength of rocks under high confining pressure was investigated. The results are very different from those of F. D. Adams, but are qualitatively checked by some more recent work of P. W. Bridgman. An increase of 1,400 per cent has been observed in the strength of marble as the confining pressure was increased from 1 to 10,000 atmospheres. Strength was also investigated as a function of time at a confining pressure of 10,000 atmospheres. A discussion is given as to which value of strength is the most important in geology. The concept of "fundamental strength" is defined.

The change in the nature of fracturing is shown as the confining pressure is increased, and also the relation between fracture and plastic flow. Contrary to common belief, experiments show that when a rock enters the region of plastic flow, it will not deform indefinitely, but will rupture if the deformation is carried far enough. Another dogma of geologists seems to be controverted by experiments. This is that sudden application of pressure is necessary to fracture a substance in the region of plastic flow. It is found that any differential pressure above the "fundamental strength" of a rock will cause fracture if the pressure is applied for a long enough time. Further, *a rock is more ductile when the differential pressure is increased rapidly than when the pressure is slowly increased.* This may afford an explanation of deep focus earthquakes.

The phenomenon of "elastic after-working" was shown in these

experiments, and is described and some of its geologic implications are pointed out.

The effect of applying a confining jacket to the specimen to keep the liquid out of the pores and thus to simulate geologic conditions is described.

The effect of deformation on rock fabric was qualitatively shown by a few experiments in which Sander's methods were utilized to study the orientation of twinning and slip planes produced by the artificial deformation.

Quartz single crystals were found to be brittle under confining pressures up to 12,000 atmospheres.

Anomalous behavior is shown in tensile and torsile tests on the Solenhofen limestone under high confining pressure. In both these tests the limestone is apparently just as brittle as at atmospheric pressure.

May it be emphasized that these results should be accepted not as principles which may be immediately applied to geology, but as a small step in our groping for the physical principles underlying structural geology. For example, the character of the relation between strength and confining pressure is such as to suggest that rocks are excessively strong at depths in the earth, and hence the forces necessary to produce deformation (such as deep-focus earthquakes) are colossal. This, however, cannot be safely inferred until the effect of time and temperature have been measured. Premature application of principles before the evaluation of the effect of all variables will delay progress immeasurably. There is every reason to believe that with patience and ingenuity every one of the geologic conditions except possibly the effect of time may be evaluated in the laboratory. When this is done, and correlations are made with field observations, structural geology may attain something more of the status of an exact science.

THE ONONDAGA FORMATION IN PENNSYLVANIA[1]

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ABSTRACT

The Onondaga formation in Pennsylvania includes all strata between the overlying Marcellus black shale and the underlying Oriskany sandstone. It consists of four members, lithologically distinct, but intergradational with one another and faunally indistinguishable. In the east a cherty limestone member overlies the Esopus shale member; in central Pennsylvania, a non-cherty limestone member succeeds a limy shale member. Local variations in lithology and thickness and minor disconformities are known. The upper contact of the formation, however, is usually transitional; and the lower contact is everywhere a disconformity. Because of its close faunal and stratigraphic affiliation with the overlying beds, the Onondaga formation in Pennsylvania is now assigned to the position of lowest formation of the Hamilton group of the Middle Devonian.

INTRODUCTION

The author's previously published studies of the Devonian of Pennsylvania have not included the Onondaga formation. It is the purpose of this paper to discuss it in some detail.

This early Middle Devonian formation was referred to as the "Corniferous" (cherty) limestone by Eaton and the "Seneca" (non-cherty) limestone by Vanuxem in western New York. The formation was subsequently called "Onondaga" by James Hall (1839).[2] This name supplanted the earlier ones and has survived. Darton (1894) gave the geographic name "Esopus" to the subjacent shale or grit which had been called "Caudi-galli" by Vanuxem (1842). Locally, the Esopus and Onondaga may be separated, as in the upper Hudson Valley, by the Schoharie grit (Vanuxem, 1840). In New Jersey the Onondaga and Esopus are known, but no Schoharie has been recognized.[3]

Both the Onondaga and Esopus have long been known in Penn-

[1] Published with the permission of the state geologist of Pennsylvania.

[2] Data on the first use of the New York terms are from Miss Winifred Goldring's account in her *Handbook of Paleontology, N.Y. State Mus. Handbook 10*, Part II (1931). We are indebted to her for suggestions on the correlation of our eastern Onondaga with the New York succession (letter of October 14, 1935).

[3] S. Weller, "The Paleozoic Faunas," *N.J. Geol. Surv. Rept. on Paleont.*, Vol. III (1903); H. B. Kümmel and J. V. Lewis, "The Geology of New Jersey," *N.J. Geol. Surv. Bull. 14* (1915).

sylvania. In 1838, a year before Hall named the Onondaga, Henry D. Rogers reported, but did not name, this limestone in Pennsylvania.[4] This appears to be the first official record of its citation in the state. In 1858 Rogers published a fuller account.[5] He called it the "Post-meridian limestone," and the subjacent Esopus became the "Post-meridian shale." Thus early, by applying the same group name to each, he recognized their close relationship. Rogers mapped them from Walpack Bend on the Delaware west to the Lehigh, where he believed they pinched out below Parryville. He recognized them in no other part of Pennsylvania.[6]

The Second Pennsylvania Survey variously reported the Onondaga limestone and Esopus shale. Different workers applied local names. The report by I. C. White on Pike and Monroe counties[7] stated that the Schoharie could not be distinguished there. He observed the transitional upper and lower contacts of the limestone and the sharp break between the Oriskany and the Esopus. The Lehigh Valley section was described by Hill.[8] In later reports details have been added.[9] The Second Survey first reported the extension of the formation west of the Lehigh. At Selinsgrove Junction, Northumberland County, I. C. White found a limestone overlying a shale between the Marcellus and Oriskany.[10] He suggested their

[4] *2d Ann. Rept. on the Geol. Explor. of the State of Pa.* (1838), p. 55: "Near the base of the olive slate formation [Hamilton], there exists a very interesting and important limestone stratum, stretching over a great range of country, from near the Delaware Water Gap, where it first obscurely shews itself, to the Helderberg mountains, southwest of Albany, and thence by a wide sweep to the westward across New York to the Falls of Niagara."

[5] *The Geology of Pennsylvania* (with state map) (1858).

[6] Rogers did mention (*4th Ann. Rept. of the Geol. Surv. of the State of Pa.* [1840]) the occurrence of limestone between the "white sandstone" (Oriskany) and the "olive slates" (Hamilton) west of the Susquehanna Valley, but he did not state the equivalence of these to his Post-Meridian of the east.

[7] "Geology of Pike and Monroe Counties," *Pa. 2d Geol. Surv.*, Vol. G6 (1882).

[8] F. A. Hill, "The Lehigh Paint Ore Mines," *Pa. 2d Geol. Surv. Ann. Rept. for 1886*, Part IV (1887), pp. 1386–1408.

[9] B. L. Miller, "The Mineral Pigments of Pennsylvania," *Pa. Topog. and Geol. Surv. Rept. 4* (1911); E. M. Kindle, "The Onondaga Fauna of the Allegheny Region," *U.S. Geol. Surv. Bull. 508* (1912).

[10] "Geology of the Susquehanna River Region in the Six Counties of Wyoming, Lackawanna, Luzerne, Columbia, Montour and Northumberland," *Pa. 2d Geol. Surv.*, Vol. G7 (1883).

correlation with the Monroe County members. Claypole called the limestone and limy shale above the Oriskany in Perry County "basal Marcellus."[11] He failed to recognize Onondaga fossils in these beds, but he did observe the break at the top of the Oriskany. D'Invilliers[12] projected I. C. White's Selinsgrove Junction divisions into Snyder, Union, Juniata, and Mifflin counties. The workers in Clinton, Lycoming, Blair, and Centre counties[13] contributed little. Ewing believed, in part rightly, that the limestone floored the Bald Eagle Valley, Centre County. The limestone reported near Lock Haven by Chance is probably the Tully.[14] In Huntingdon County, I. C. White again found his Selinsgrove Junction succession.[15] Farther south, J. J. Stevenson, failing to distinguish the Onondaga in Bedford and Fulton counties, treated it as basal Marcellus.[16] At the close of the nineteenth century Prosser's work in the upper Delaware Valley added little.[17] When Lesley summarized the work of the Second Pennsylvania Survey,[18] he gave a full account of both the Onondaga limestone and shale

The twentieth century has seen a few contributions. Stose and Swartz[19] recorded provisionally as Onondaga the basal member of the Romney formation along the Maryland-Pennsylvania line.

[11] E. W. Claypole, "A Preliminary Report on the Palaeontology of Perry County," *ibid.*, Vol. F2 (1885).

[12] E. V. D'Invilliers, "Report on the Geology of the Four Counties of Union, Snyder, Mifflin and Juniata," *ibid.*, Vol. F3 (1891).

[13] H. M. Chance, "The Geology of Clinton County," *ibid.*, Vol. G4 (1880); A. Sherwood, "The Geology of Lycoming and Sullivan Counties," *ibid.*, Vol. G2 (1880); F. Platt, "The Geology of Blair County," *ibid.*, Vol. T (1881); A. L. Ewing, "The Geology of Centre County," *ibid.*, Vol. T4 (1884), Appendix B.

[14] Bradford Willard, "Tully Limestone and Fauna in Pennsylvania," *Geol. Soc. Amer., Preliminary List of Titles and Abstracts of Papers To Be Offered at the 48th Annual Meeting* (1935), abst., p. 71.

[15] "The Geology of Huntingdon County," *Pa. 2d Geol. Surv.*, Vol. T3 (1885).

[16] "The Geology of Bedford and Fulton Counties," *ibid.*, Vol. T2 (1882).

[17] C. S. Prosser, "The Devonian System of Eastern Pennsylvania and New York," *U.S. Geol. Surv. Bull. 120* (1895).

[18] J. P. Lesley, "A Summary Description of the Geology of Pennsylvania," *Pa. 2d Geol. Surv.*, Vol. II (1892), pp. 1034–1193 (Oriskany, Esopus, and Onondaga).

[19] G. W. Stose and C. K. Swartz, "Description of the Pawpaw and Hancock Quadrangles," (Md., W. Va., and Pa.), *U.S. Geol. Surv. Folio 179* (1912).

Butts[20] reported 50 feet of Onondaga shale and limestone near Altoona. The most comprehensive account, and the only one with faunal details, is by Kindle.[21] Because he described the formation from New York to Virginia, few local details could be given. Some casual references to the Onondaga have appeared recently. Willard mentioned limestone and shale at Selinsgrove Junction.[22] Willard and Cleaves and, later, Willard alone, in describing the Hamilton group in Pennsylvania, recorded occurrences of the Onondaga from New Jersey west to Bedford County.[23] Cleaves studied the geology of the New Bloomfield quadrangle (Perry County), and his unpublished manuscript map and his notes on the Onondaga have been used in this account. Subsurface data by Fettke for northern Pennsylvania[24] record the Onondaga from Warren County to Bradford County. He announced 196 feet of Schoharie in the east.

DISTRIBUTION

The Onondaga formation in Pennsylvania is here defined to include all stratigraphic units between the overlying Marcellus and the underlying Oriskany formations. It is faunally and lithologically closely allied with the Hamilton group and is quite distinct from the Oriskany. Therefore, it is proposed to include it in the Hamilton group of the Middle Devonian. In Pennsylvania the formation usually consists of two facies, limestone above and shale below. These in themselves vary and contain local units of minor importance.

Figure 1 shows the distribution of the Onondaga formation in central and eastern Pennsylvania. In parts of Fulton County the

[20] Charles Butts, "Geologic Section of Blair and Huntingdon Counties, Central Pennsylvania," *Amer. Jour. Sci.*, 4th ser., Vol. XLVI (1918), pp. 523–37.

[21] *Op. cit.*

[22] Bradford Willard, "The Devonian Section at Selinsgrove Junction, Pennsylvania," *Amer. Midland Nat.*, Vol. XIII (1932), pp. 222–35.

[23] Bradford Willard and A. B. Cleaves, "Hamilton Group of Eastern Pennsylvania," *Geol. Soc. Amer. Bull. 44* (1933), pp. 757–82; Bradford Willard, "Hamilton Group of Central Pennsylvania," *Geol. Soc. Amer. Bull. 46* (1935), pp. 195–224, and "Hamilton Group along the Allegheny Front, Pennsylvania," *ibid.*, pp. 1275–90.

[24] C. R. Fettke, "Subsurface Devonian and Silurian Sections across Northern Pennsylvania and Southern New York," *Geol. Soc. Amer. Bull. 44* (1933), pp. 601–60.

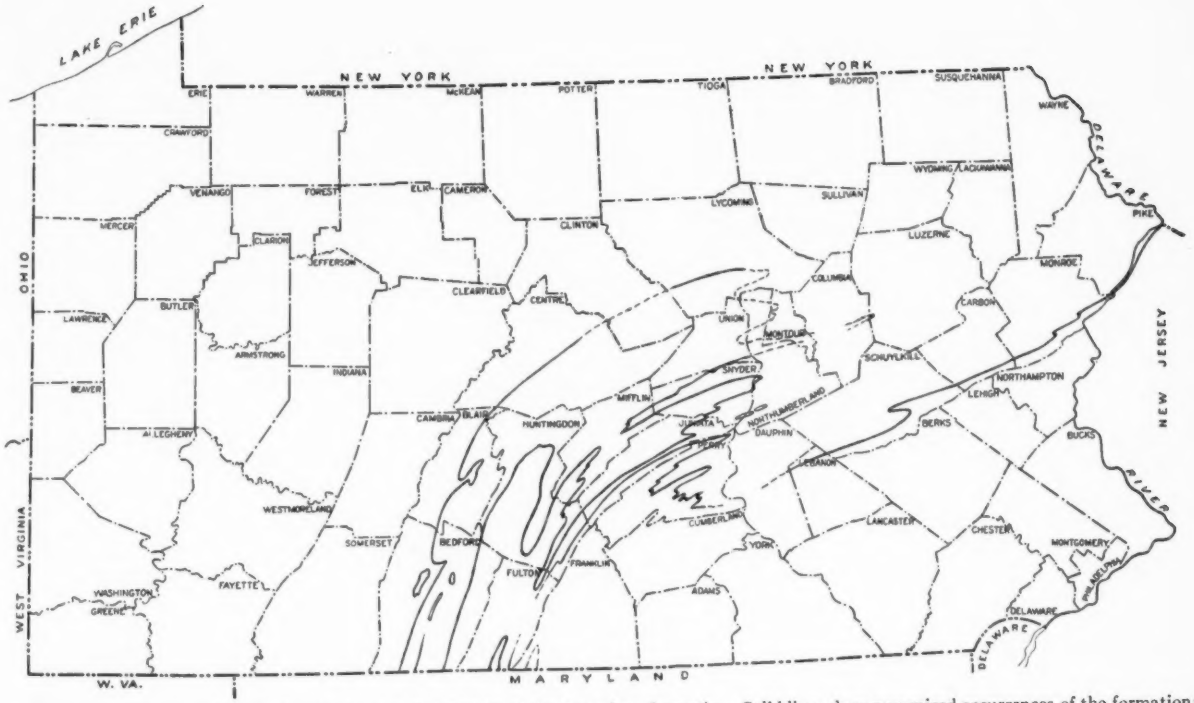

FIG. 1.—Sketch map of Pennsylvania showing distribution of the Onondaga formation. Solid lines show recognized occurrences of the formation; broken lines show localities where its presence is inferred.

Onondaga is removed from the section by faulting. It might be expected to cross and recross Columbia and Montour counties, but has not been recognized there, though it has been recorded near Beach Haven, west-central Luzerne County. The author has not found the Onondaga in Clinton County; and it has been only doubtfully identified in Centre County, though it is probably present under the glacial drift and débris of the Susquehanna and Bald Eagle valleys. No Onondaga is present on the Susquehanna in western Dauphin or southeastern Perry counties.

DESCRIPTION

Though the divisions of the Onondaga formation in Pennsylvania (Table I) are lithologically distinct, they intergrade, and are so closely allied faunally that the whole may be looked upon as an entity. Minor, local variations are recognized.

TABLE I

DIVISIONS OF THE ONONDAGA FORMATION

Central Pennsylvania	Eastern Pennsylvania
1. Upper member, non-cherty limestone, called Selinsgrove* lower limestone by I. C. White	1. Upper member, cherty limestone, called Post-meridian* by Rogers, Corniferous or Upper Helderberg* by I. C. White
2. Lower member, limy shale, called Selinsgrove* shale by I. C. White	2. Lower member, Esopus shale, called Post-meridian* by Rogers, Caudi-galli* by I. C. White

* Name discarded.

Upper member, cherty limestone.—This member is developed best in Monroe County and occurs also in Carbon and Pike counties in eastern Pennsylvania. About 200 feet thick in south-central Monroe, it thins rapidly westward and is last recognized as a 5-foot bed on the Lehigh River in south-central Carbon County. Cherts have been reported in the upper limestone member from farther west, but are at best scattered or local. This cherty limestone is most like the eastern New York type, into which it is probably traceable. It is usually massive, dark- or blue-gray limestone whose outstanding feature is the great quantity of dark chert present as nodules from 2–3 inches in diameter up to occasional masses a foot across. Mostly

lenticular, they are oriented parallel to the stratification, and may produce nearly continuous beds. Probably no part of this limestone is free from chert, but the chert seems to be most abundant in the middle 50 or 100 feet, and dies out upward and downward. Where poor in chert, the limestone may be strongly sheared. Good exposures of this member are obtained in abandoned quarries and road cuts between Stroudsburg and Bushkill and at Buttermilk Falls. A splendid section is seen on the Delaware, Lackawanna, and Western Railroad, ½ mile south of East Stroudsburg station. Here the limestone passes down gradually into the Esopus shale, with loss of chert and, *pari passu*, dominance of shale over limestone. The limestone changes gradually upward into the Marcellus shale. Loss of chert is accompanied by transition from gray, shaly limestone to black, fissile shale. This may be studied between the Stroudsburg station of the New York, Susquehanna, and Western Railroad and the nearby creek bed. The cherty member produces but little topographic expression. Usually, with the Marcellus, it underlies a valley, but may rise in small hogbacks or support cliffs in eastern Monroe County.

The fauna is characteristically Onondagan, strongly Middle Devonian. Corals are more numerous in this than any other part of the formation in the state. The chert makes collecting difficult, but weathered surfaces may yield well-preserved remains. A further discussion and tabulation of the fauna will be found under "Correlation."

Lower member, Esopus shale.—This shale is known in eastern Pennsylvania only and has been considered a separate formation.[25] Upon evidence to be cited, we prefer to include it in the Onondaga formation as a distinct unit. Absent from Pike County, it enters the state at Walpack Bend, and has a distribution similar to the cherty limestone. It is best developed in Monroe County, where it is about 250 feet thick, thinning rapidly westward to between 4 and 10 feet in the Lehigh Valley; it is not identified beyond Carbon County. The lithology is characteristic—unvarying, dark, ashen-gray to brown, gnarly or sandy shale. Some beds may be limy. A peculiarity is its tendency to shear strongly. Some of the best exposures are

[25] Kümmel and Lewis, *op. cit.*

to be had on the new highway south of Stroudsburg across Godfreys Ridge and along the railroads up Brodhead Creek Valley. The structure here is complex, but the relations to the Oriskany may be studied. The latter ends above in coarse, even pebbly sandstone with characteristic fossils. The basal Esopus is lithologically characteristic and barren save for perhaps an occasional *Taonurus*. This fossil (from which the old name "Caudi-galli" grit came) is probably more common than generally supposed in the Esopus of Monroe County, where intense shearing has tended to obliterate it. The few fossils of the Esopus, except *Taonurus*, occur chiefly in the upper half. They are forms indistinguishable from those of the other parts of the Onondaga. The Schoharie is unknown. The Onondaga limestone and the Esopus shale east of Carbon County intergrade lithologically, but the shale rests disconformably on the Oriskany. The faunal evidence supports the lithologic relations. Since the Esopus is thus closely allied with the cherty limestone, but only remotely related to the Oriskany, it is grouped with the Onondaga formation. The former grouping of the Esopus with the Oriskany appears to have been upon physiographic, rather than stratigraphic or paleontologic, evidence.

Upper member, non-cherty limestone.—This member occurs most widely in central Pennsylvania. It appears first in Carbon County as some 20 feet of "hydraulic cement rock." Westward, it becomes the characteristic upper member of the Onondaga formation, and there bears the same relative position which the cherty phase assumes farther east.[26] The absence of chert is the chief difference between this limestone and the eastern upper member. It is medium to dark gray, usually soft, tends to be thin-bedded, and may be quite shaly. At Selinsgrove Junction in Northumberland County are some

[26] This is the unit which I. C. White named the "Selinsgrove lower limestone" (I. C. White, "The Geology of the Susquehanna River Region in the Six Counties of Wyoming, Lackawanna, Luzerne, Columbia, Montour and Northumberland," *Pa. 2d Geol. Surv.*, Vol. G7 [1883], pp. 78–81). Among other divisions he listed the following: Selinsgrove upper sandstone, Selinsgrove lower sandstone, Selinsgrove upper limestone, Selinsgrove lower limestone, Selinsgrove shale.

The upper and lower sandstones and the upper limestone are assignable to the Hamilton group (the limestone is of Marcellus age). The lower limestone is unquestionably Onondaga in age. The shale below it intervenes between the limestone and the top of the Oriskany.

fairly massive beds. Weathered outcrops are often difficult to tell from the underlying limy shale member, as both may alter to an olive-drab, spongy or punky residuum. The thickness at Selinsgrove Junction, 65 feet, appears to be close to the maximum. Southeastward it is 7 feet in Lebanon County, 20 feet in Carbon, and is indistinguishable farther east, where it is thought to merge with the cherty phase. Southwest and west of Northumberland County, the non-cherty Onondaga limestone is widespread, 35–40 feet thick in Perry County and about 30 feet in northern Bedford; but is not recognized farther south into Maryland, as it grades into limy shale inseparable from the subjacent member. It probably continues through Mifflin into Clinton and Centre counties but was not definitely identified in the last two. It has been recognized in Lycoming County on the highway west of Jersey Shore and eastward. The fauna of this member is more abundant than that of the cherty limestone, though corals are rarer. Its Onondaga relations may be seen in the faunal chart given in the section on "Correlation."

The limestone everywhere grades downward into the underlying shale where that is present. The relations to the Marcellus vary. In south-central areas, chiefly Bedford and Fulton counties, the contact is gradational and similar to the transition between the cherty limestone and the Marcellus in the east. But, throughout central Pennsylvania, in the Susquehanna and lower Juniata valleys, other conditions persist. In southeastern Perry and west-central Dauphin County, the Marcellus rests upon Upper Silurian red beds, probably owing to erosion in early Hamilton time.[27] West and northwest of central Perry County, the limestone may stop abruptly at a poorly developed, basal Marcellus iron ore. In Perry County at Half Falls Mountain on the Juniata River (Fig. 2) and north of Thompsontown, Juniata County, on Delaware Creek and on into Snyder County, the top of the limestone ends sharply. Its upper surface appears in places as small rounded bosses suggesting weathering. Upon this are found 1–16 inches of friable, brown, micaceous, ferruginous sandstone which intergrades with the Marcellus black shale.

The non-cherty limestone dies out suddenly east of Northumber-

[27] Willard, "Hamilton Group of Central Pennsylvania," *loc. cit.*

land County. Exposed at the Montour-Columbia county line on a secondary road south from U.S. Route 11, between the Marcellus and Oriskany is 4 or 5 feet of barren, reddish, residual clay with chert fragments. This may have been derived from the Onondaga or the Oriskany, or both. On Big Fishing Creek north of Bloomsburg the Marcellus is faulted against the Upper Silurian (Tonolo-

FIG. 2.—Quarry in Onondaga non-cherty limestone at Half Falls Mountain, west bank Juniata, Perry County. Black Marcellus shale at top. Arrow marks contact of the Marcellus with the Onondaga. Photograph by George H. Ashley.

way) limestone.[28] On the same stream south of the town the basal Marcellus black shale and the top of the New Scotland (?) member of the Helderberg are exposed. A little coarse sandstone (Oriskany?)

[28] The identity of this limestone has been established by Dr. Frank M. Swartz (personal communication).

separates them, but no Onondaga was identified. White[29] believed that the Oriskany pinched out east of here; the Onondaga appears to do so too. In Luzerne County just east of the Columbia line near Beach Haven a small exposure of impure limestone is probably the Onondaga. This, and more seen at low water in the river under Berwick bridge, may represent the formation at the eastern tip of the Berwick anticline. Throughout central Pennsylvania the Marcellus-Onondaga contact is thus disconformable. Perhaps the varying thickness of the limestone (Fig. 5) signifies that the interval of non-deposition between the formations continued longer in some places than others.

Lower member, limy shale.—This is the fourth Onondaga member recognized in Pennsylvania, and is the dominant type for the lower part of the formation in the central region. It is the downward continuation of the non-cherty limestone, differentiated therefrom by a decided reduction in calcareous, and an increase in argillaceous, content. Dark to medium gray, it has been described as green or greenish. Our experience is that these shades develop only on exposure. Thin, gray-to-black limestones are omnipresent, and may increase upward until they dominate as the upper member. In central Pennsylvania sandy beds appear and increase southwestward as the Onondaga formation disappears under the Allegheny front. Sand grains are sometimes found in the limestones as well as in the shale. In the southern sections, the Onondaga limy shale is 100–150 feet thick. It maintains its thickness generally west of the Susquehanna (Fig. 5), and is 140 feet thick in western Northumberland County, thins south into Perry, is gone in Dauphin, reappears in Schuylkill, but is seen no more as such eastward. The Onondaga limy shale member is probably present in Centre and Clinton counties and has been found in Blair and Lycoming. From 140 feet in Northumberland County, it thins to nothing in Columbia, a condition strictly analogous with that observed for the succeeding non-cherty limestone. It may be present near Beach Haven, Luzerne County. Many good exposures of this member are seen in central Pennsylvania, particularly in Snyder, Union, and Mifflin counties.

[29] "The Geology of the Susquehanna River Region in the Six Counties of Wyoming, Lackawanna, Luzerne, Columbia, Montour, and Northumberland," *loc. cit.*, pp. 221 ff.

The exceptional section at Newton Hamilton in Mifflin County is given in detail on a later page.

The upper contact of the limy shale with the non-cherty limestone is gradational. Where the limestone is indistinguishable, the shale intergrades with the Marcellus. A fine exposure on the highway north of Warfordsburg, Fulton County, clearly shows the limy shale–Marcellus contact. The lower contact is a disconformity, as is that of the Esopus, with the Oriskany. The Oriskany is commonly a coarse, often weak, friable sandstone terminating abruptly upward. The faunal change is likewise striking. At some localities from Perry County west and northwest a thin limonitic bed lies at the contact.[30] This is well exposed at the cemetery at New Bloomfield, Perry County, and between Fort Littleton and Hustontown, Fulton County, and elsewhere. Resting upon the sandstone, the limonite may have originated through a process of enrichment during an Oriskany-Onondaga interval. In western Mifflin County a remarkable contact is seen on the Pennsylvania Railroad at Newton Hamilton (Fig. 3). Here the limy shale is thick with a thin limestone at its base which rests directly upon the uneven top of the Oriskany. Grains derived from the sandstones are abundant in the limestone, but no angular discordance of dips was measured.

The Onondaga limy shale is highly fossiliferous, more so than the non-cherty limestone. It is clearly Middle Devonian with Onondaga diagnostics. Faunally, it is in striking contrast with the Oriskany. Its total identified fauna and that of its black shale variant are given in the table in the section on "Correlation."

The withdrawal of the sea at the end of Oriskany time throughout central Pennsylvania was followed by an interval of non-deposition. Sometimes erosion took place, or weathering may have concentrated a little iron ore. Probably erosion was seldom deep, save in restricted areas, for where the Oriskany occurs it seems to be represented by both its upper and lower members. We may note that the Onondaga formation is absent in southeastern Perry and west-central Dauphin counties, and thence northeastward toward Columbia. Ap-

[30] E. W. Claypole, "A Preliminary Report on the Palaeontology of Perry County, etc.," *Pa. 2d Geol. Surv.*, Vol. F2 (1885); J. H. Dewees and C. A. Ashburner, "Report of Progress in the Juniata District, etc.," *ibid.*, Vol. F (1878).

parently from this restricted region the Oriskany, too, is usually absent. Observing (Figs. 1 and 5) that this region from which the beds are gone is relatively narrow and elongated, we may imagine that it represents an erosion channel, from which the Oriskany and Onondaga were removed in early Marcellus time prior to the deposition of a delta which came to occupy this area during the later Middle Devonian.[31]

FIG. 3.—Oriskany-Onondaga contact on the Pennsylvania Railroad at Newton Hamilton, Mifflin County. The hammer indicates the disconformity. At the base of the shale occurs a thin limestone carrying sand grains derived from the Oriskany. Shale slumping from above tends to obscure the base of the Onondaga. Photograph by the author.

Minor variations of the Onondaga formation.—Among the members of the Onondaga formation in Pennsylvania are a few variations. Iron ores reported at the base and top appear to be best assigned to the Oriskany and Marcellus, respectively. So far as we know, nothing comparable to the Schoharie outcrops in Pennsylvania. In the Lehigh Valley in the region of Bowmanstown, paint ores have long been dug from the Onondaga. The section there based upon various

[31] Willard, "Hamilton Group of Central Pennsylvania," *loc. cit.*

accounts is given approximately in Table II. The ore has been described by Miller:[32]

> The ore resembles impure blue limestone, but without distinct bedding or joint planes and were it not for the high specific gravity, it would scarcely be thought to possess any value. It is dark blue in color when fresh, but on being exposed to the air soon reddens due to the oxidation of the iron originally present in the form of the carbonate.

All specimens which we have examined effervesce in cold, dilute hydrochloric acid. The ore is very fossiliferous, and unmistakably

TABLE II

	Feet
Hamilton group	
Onondaga cherty limestone	5
Onondaga non-cherty limestone	20
Paint ore	2– 4
Esopus shale or clay	4–10
Oriskany sandstone	

Onondaga. Miller[33] listed a few fossils. Now, thanks to an opportunity to study the Lehigh University collection, we are able to list a quite large fauna (see tabulation of faunas under section on "Correlation"). This list is interesting because of the meagerness of the corals, the low percentage of mollusks, and the unusually large number of trilobites. Preservation is exceptionally fine.

The ore intergrades with the overlying limestone but is sharply separable from the Esopus. Here we have the unique occurrence of a local disconformity at the top of the Esopus, and also the presence of both limestone phases in the same section. The Esopus, recognized through abundance of *Taonurus*, is itself in disconformity with the Oriskany, as the lithologic and faunal changes are sharp. Presumably, the post-Esopus interval may include the limy shale to the west, unless that shale can be correlated with the paint ore.

In western Mifflin County and in nearby sections, as in Lycoming County at Jersey Shore, and elsewhere, the lower Onondaga contains much black shale. This rock is very similar to the Marcellus litho-

[32] Miller, *op. cit.*, pp. 48–68.

[33] *Ibid.*

logically but differs faunally.[34] The partly composite section on the Pennsylvania Railroad at Newton Hamilton given in Table III shows the succession. Both the limy beds and the black shale carry an

TABLE III

MARCELLUS-ONONDAGA SECTION AT NEWTON HAMILTON

	Feet
a) Marcellus black shale, exposed	39
b) Onondaga non-cherty limestone; sandy, gray, brown-weathering, carries pyrite nodules. Well-rounded sand grains present. Fossiliferous	4
c) Onondaga non-cherty limestone; gray, massive with impure black shale partings in midst. Conchoidal fracture	1–2
d) Onondaga limy shale; here dominated by black, fissile shale with large, calcareous concretions, some more or less continuous limestone beds merging into the limestone above (Fig. 4)	19
e) Same as (*d*) but concretions fewer and more scattered; shale often limy looking; no concretions from 40 feet below (*d*) to base of (*e*), but thin, sandstone partings present in lower part	78
f) Similar to (*e*) but concretions again plentiful, though here appear sandy and show shale laminations on weathered surfaces. Unweathered concretions consist of dense, black limestone	22
g) Similar to (*f*); concretions rare, but large, up to 5 feet long and may show septarian structure. They become more abundant in the lower part	67
h) Black shale and gray interbeds of platy to massive limestone 3–4 inches thick. Limestone dominant in lower 10 feet of this unit	17
i) Oriskany sandstone, exposed	5

Onondaga fauna with strong Middle Devonian affinities. Most of the black shale fossils are small mollusks, including coiled cephalopods, elsewhere rare in the Onondaga of Pennsylvania. This fauna has not been completely studied, but Table IV serves to show its

[34] Throughout Pennsylvania it has been our experience that, where there is any question as to the Onondaga-Marcellus boundary, the faunas may be distinguished through the presence of *Anoplotheca acutiplicata* in the one and *Liorhynchus limitare* in the other.

composition. Considering the geographic distribution of the black shale facies, this occurrence appears to be the eastern edge of such a development which may extend widely westward beneath great thicknesses of later rocks. It is interesting to compare this northwestward development of the black shale with the southwestward increase in sandy material in the Onondaga shale, and from these and the distribution of the limestones to infer the paleogeography.

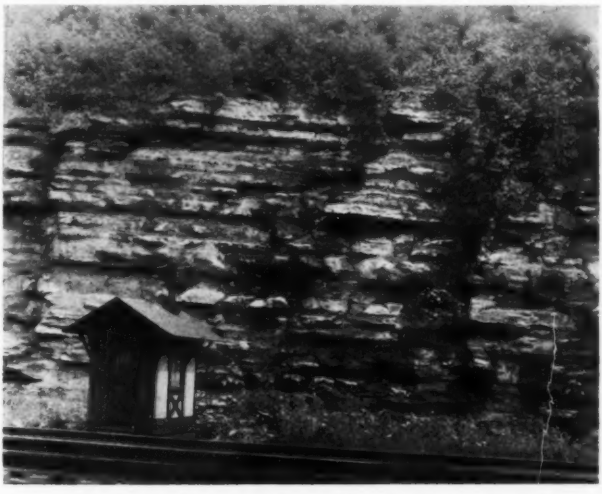

FIG. 4.—Upper part of black Onondaga shale at Newton Hamilton. Limestone is here becoming dominant. Photograph by the author.

CORRELATION

Intrarelations.—The Onondaga formation in Pennsylvania, though divisible into four members, shows close affinities as a united whole and is intimately related to the overlying Hamilton group. Already we have seen that everywhere the Onondaga is succeeded by the Marcellus black shale through a normally transitional contact which may become disconformable locally. Studies of the Marcellus, except where it is incomplete, show its base to be essentially synchronous throughout. Below, the Onondaga limy shale and the Esopus shale are in disconformity with the Oriskany. Except where

local erosion has been great, the top of the Oriskany probably is represented by beds belonging to its upper, or Ridgely, member. Thus, the upper and lower limits of the Onondaga are definitely established. If we next consider the several members, we note that the non-cherty limestone and the limy shale of the central sections are transitionally interrelated. Likewise, the cherty limestone and the Esopus shale in the east intergrade. All four members carry essentially the same fauna, though it is more abundant in some than

TABLE IV

ONONDAGA BLACK SHALE FAUNA, MIFFLIN COUNTY*

Lingula, sp.
Orbiculoidea lodiensis, var. *media*.
O., sp.
Chonetes buttsi
Anoplotheca acutiplicata
Panenaka, sp.
Nuculites triquiter
Palaeoneilo, cf. *emarginata*
Conocardium, sp.
pelecypod, undetermined
Pleurotomaria lucina
Buchanopsis lyra
Naticopsis, sp.
Platyceras, sp.
Styliolina fissurella
Conularia undulata
Bactrites aciculum
Orthoceras, sp.
Agoniatites expansus
Goniatites, undetermined
Phyllocarid, undetermined
Pisces, undetermined spines and "bone" fragments

* In Table V in the section on "Correlation," a complete list of fossils from all black shale exposures studied is given.

others. This is illustrated in Table V. The limestones have a somewhat reduced fauna; the limy shale and the paint ore are the most fossiliferous beds; and the Esopus has the fewest fossils, found mostly in its upper half. The strong Hamilton affinities of the Onondaga fauna have been noted previously. Most of the fossils continue on into later beds; some, such as *Anoplotheca acutiplicata*, are unknown above the Onondaga in Pennsylvania. Of the few fossils found in both the Onondaga and Oriskany, most are long-range species which are found also above the Onondaga.

The section on the Lehigh River in Carbon County furnishes a key to the relations between eastern and central areas. This is shown in Table VI.

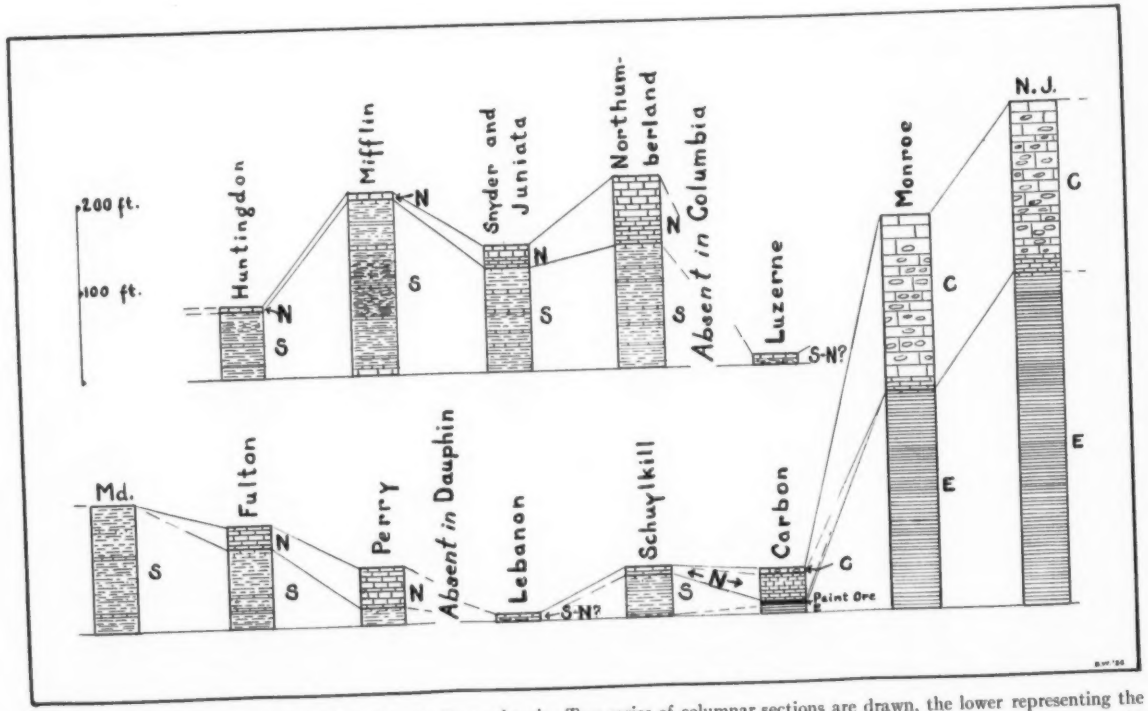

FIG. 5.—Correlation chart of the Onondaga in Pennsylvania. Two series of columnar sections are drawn, the lower representing the Onondaga in the more southern counties; the upper, the formation across central Pennsylvania. *C*=cherty limestone, *E*=Esopus shale, *N*=non-cherty limestone, *S*=limy shale. New Jersey and Maryland sections are included for comparison.

TABLE V

TABLE OF ONONDAGA FAUNAS OF PENNSYLVANIA

Fauna	Cherty Limestone	Non-cherty Limestone	Limy Shale*	Black Shale	Paint Ore	Esopus Shale	New Jersey, Composite	Maryland, Composite
Sponge, undetermined		×			×			
Streptelasma, sp.			×					
Zaphrentis simplex	×	×	×					
Z. prolifica		×	×					
Z., sp.	×	×	×		×		×	
Amplexus hamiltoniae			×					
A., sp.					×			
Cystiphyllum, sp.	×							
Cyathophyllum, sp.	×							
Favosites, sp.	×					×		
Ceratopora, sp.			×					
Cladopora, sp.	×							
Corals, undetermined	×	×	×					
Polygnathus, sp.								×
Taonurus, sp.		×				×		
"Crinoidea," columnals	×	×	×		×			
Hederella, sp.					×			
Cystodictya gilberti		×						
Fenestella, sp.	×	×			×		×	
Polypora, cf. *distans*		×						
P., cf. *hexagonalis*		×						
Conscinium, cf. *striaturum*		×						
Bryozoa, undetermined			×		×			
Lingula ligea			?					
L. delia		?						
L., cf. *nuda*								×
L., sp.		×		×	×	×	×	
Orbiculoidea lodiensis, var. *media*		×	×	×				×
O., sp.			×	×		×		
Craniella hamiltoniae								×
Pholidops, cf. *areolata*			×					×
Pholidostrophia pennsylvanica		?	×					×
Leptostrophia perplana	×	×	×		×		×	×
L., sp.			×					
Stropheodonta patersoni				×	×			
S. inequistriata		×	×		×			
S. concava					×			
Douvillina, sp. nov.				×				
Leptaena rhomboidalis	×	×			×		×	

* Exclusive of black shale and paint ore facies, which are listed separately. Of the 115 specifically identified fossils in the foregoing list, 63 per cent have been recorded from later Middle Devonian formations, 26 per cent are confined to the Onondaga group (including the Schoharie), and 11 per cent have been reported from the Oriskany or older Devonian formations. Of these last, about half range on into beds above the Onondaga.

TABLE V—*Continued*

Fauna	Cherty Limestone	Non-cherty Limestone	Limy Shale*	Black Shale	Paint Ore	Esopus Shale	New Jersey, Composite	Maryland, Composite
Leptaenisca australis			×					×
Schuchertella pandora			×		×		×	×
S., cf. *perversa*		×	×					×
S. variabilis								×
Chonetes mucronatus	×	×	×		×			×
C. hemisphericus		×						
C. buttsi		×	×	×				
C., cf. *setiger*			×					
C. coronatus			×					
C. scitulus			×					
C., cf. *lepidus*					×			
C. arcuatus			×		×		×	
C. rugosus								×
C., sp. nov.				×				
C., sp.	×	×	×	×		×		
Anoplea nucleata		×	×					×
Strophalosia truncata		×	×					×
Productella navicella		×						
P., sp.			×					
Dalmanella lenticularis			×		×			×
D., sp.			×		×			
Rhipidomella vanuxemi		×	×		×		×	×
R. leucosia					×			×
R. cyclas								×
R. (?)					×			
Camarotoechia, sp.		×						
Centronella, cf. *ovata*								×
Cranaena romingeri		×						
Liorhynchus, cf. *multicosta*			×					
L., sp.			×					
Tropidoleptus, sp.			×					
Atrypa reticularis	×	×	×		×		×	
A. spinosa	?							
Cyrtina hamiltonensis	×		×					
C., sp.			×					
Spirifer, cf. *varicosus*		×					×	
S. raricostus			×					
S. acuminatus		×						
S. macrothyris					×			
S., cf. *octocostatus*			×					
S., sp.		×			×	×		
Elytha fimbriata			×				×	×
Ambocoelia umbonata		×	×					×
A. nana			×					
A., sp.		×	×					
Nucleospira concinna			×					×
Anoplotheca acutiplicata	×	×	×	×		×	×	×
A. concava							×	
A. camilla		×		×				×
A., sp. nov.		×	×					

TABLE V—*Continued*

Fauna	Cherty Limestone	Non-cherty Limestone	Limy Shale[a]	Black Shale	Paint Ore	Esopus Shale	New Jersey, Composite	Maryland, Composite
Martinia? sp.		×						
Vitulina pustulosa			?					
Pentagonia unisulcata	×	×						
Pentamerella arata					×			
Brachiopoda, undetermined		×	×			×		
Euthydesma, sp.								×
Panenka alternata								×
P., cf. *dichotoma*								×
P., obsolescens								×
P., cf. *multiradiata*			×					×
P., sp.			×	×				
Buchiola halli								×
Nucula corbuliformis			×					×
N., sp.			×					
Nuculites modulatus			×					×
N. triqueter				×				×
Palaeoneilo constricta			?					×
P. emarginata				?		×		
Liopteria sayi			×					
L. laevis								×
Conocardium, sp.	×			×				
Actinopteria, sp.		×						
Schizodus, sp.		×						
Aviculopecten equilatera								×
Modiomorpha subalata								×
M., sp.			×					
Pelecypoda, undetermined				×				
Pleurotomaria lucina				×				
P. crassa		×						
P., sp.			×					
Bellerophon leda		×						
B., cf. *pelops*			×					
B., sp.			×					
Buchanopsis lyra				×				
Naticopsis, sp.			×	×				×
Loxonema hamiltoniae								×
L., cf. *pexata*			×					
L., sp.			×				×	
Platyceras, sp.	×		×	×			×	
Diaphorostoma lineatum			×					
Platystoma, cf. *euomphaloides*								×
P., sp.		×		×	×			
Styliolina fissurella		×	×	×				×
S., sp.		×	×	×				
Tentaculites bellulus	×	?						
T., sp.			×					
Conularia undulata				×				?
C., sp.				×				

TABLE V—*Continued*

Fauna	Cherty Limestone	Non-cherty Limestone	Limy Shale*	Black Shale	Paint Ore	Esopus Shale	New Jersey, Composite	Maryland, Composite
Enchostoma, sp.								?
Coleolus curvatus			×					
C. tenuicinctus				×				
Hyolithus, cf. *aclis*			×					
H., cf. *principalis*			×					
Orthoceras, cf. *subulatum*			×					
O., sp.		×	×	×				
Bactrites aciculum		×	×	×				×
B., sp.				×				
Paradisceras discoideum								×
Agoniatites expansus								×
Goniatites, undetermined		×	×	×		?		×
Cephalopoda, undetermined			×					
Proëtus, sp.			×					
Acidaspis callicera			×		×			
Phacops cristata		×	×		×			×
P. cristata, var. *pipa*		×	×				×	×
P. rana		×	×		×		×	
P. bufo	?							
P., sp.		×	×				×	
Dalmanites boothi, var. *calliteles*		×	×					
D. aspectans		×	?					
D. anchiops						×		
D., sp.		×	×		×			
Odontocephalus selenurus		×					×	
O. aegeria		×	×		×		×	
O. cristata			×					
O., sp.			×					
Lichas, sp.					×			
Cyphaspis, cf. *stephanophora*								×
C. minuscula					×			
Phaëthonides gemmaeus					×			
Trilobita, undetermined		×						
Leperditia? cf. *subrotunda*			×					×
Bollia ungula			×					×
B? obsea			×					×
B., sp.			×	×				
Bythocypris favulosa			×					
B., sp.			×					
Ulrichia conradi			×					
Octonaria stigmata			×					
Ostracoda, undetermined		×	×		×			
Phyllocarida, undetermined				×				
Pisces, undetermined				×				
Plantae, undetermined			×					
Fucoids						×		

The cherty and non-cherty limestones intergrade at the Lehigh. They are nearly, if not precisely, equivalent. This relationship is supported further by their contacts with the Marcellus, their faunal content (corals being numerically most abundant here), and their passage into the underlying beds which are themselves invariably a definite unit separated in turn from the Oriskany by a disconformity. Similarly, the limy shale and the Esopus may be correlated. Both rest disconformably on the Oriskany, and each grades upward into one or the other of the two equivalent limestones. Their respective faunas show no marked differences save in relative abundance.

TABLE VI

Central Pennsylvania	Lehigh Valley	Monroe County
Marcellus shale	Marcellus shale	Marcellus shale
Transition (usually)	Transition	Transition
Onondaga non-cherty limestone	Onondaga cherty limestone Transition Onondaga non-cherty limestone	Onondaga cherty limestone
Transition	Transition	Transition
Onondaga limy shale	Paint ore Disconformity Esopus shale	Esopus shale
Disconformity	Disconformity	Disconformity
Oriskany formation	Oriskany formation	Oriskany formation

The paint ore is correlated with the upper part of the limy shale to the west and the upper Esopus to the east of the Lehigh, for it occupies the same relative position in section. It intergrades with the overlying limestone, as do the limy shale and the Esopus. Its fauna is plentiful, as is that of the limy shale; and both include a greater abundance of trilobites than has been encountered in the other Onondaga members.

A local disconformity between the base of the paint ore and the Esopus cuts out most of the latter or any characteristic limy shale. We may assume that the ore represents a local accumulation of abnormal sediments following a brief and geographically restricted interruption. The almost total absence of mollusks suggests an exceptional environment. Bedding is lacking; but the fossils are not re-

placed by mineralization, nor are they distorted. The trilobites are remarkably well preserved, and the brachiopods are not disarticulated. The condition of the fossils is taken to indicate syngenetic rather than epigenetic origin of this deposit.

Interrelations.—We have seen that the cherty limestone and Esopus shale in the east are traceable into identical equivalents in northwestern New Jersey and probably can be directly correlated with the New York sections. The limy shale which may represent the entire Oriskany-Marcellus interval in the south-central counties becomes the "Onondaga member" of the "Romney formation" in Maryland.[35] For this reason and because of lithologic and faunal relations throughout Pennsylvania, we propose now to include the Onondaga formation with the Hamilton group as its lowest major division. Our only reason for not having done so previously has been the evidence of an Onondaga-Marcellus break in central Pennsylvania. Since this is now found to be local, there remains no valid reason for excluding the Onondaga from the Hamilton group. The correlations with New Jersey and Maryland are fully borne out by the faunas from each state listed in Table V.

Before leaving the correlation, attention should again be called to Fettke's article on the interpretation of well records in our northern tier of counties.[36] His reported 196 feet of "Schoharie" in Bradford County appears from the lithology to be more truly the Onondaga limy shale, but such a designation is without support other than lithology and deduced distribution. We are inclined to regard our Esopus as the near-shore, more coarsely clastic equivalent of the limy shale. With clearing of the waters, limestone succeeded the shale in the east and west simultaneously. Why is one chert-free and other cherty? If the eastern facies was laid down near shore, it might be assumed that silica gel was precipitated there in late Onondaga time but failed to spread far to sea. This, of course, assumes the Onondaga cherty and calcareous constituents to have been formed simultaneously. If the chert be epigenetic, a quite dif-

[35] Stose and Swartz, *op. cit.;* C. S. Prosser, E. M. Kindle, and C. K. Swartz, "The Middle Devonian Deposits of Maryland," *Md. Geol. Surv., Middle and Upper Devonian* (1913).

[36] *Op. cit.*, pp. 654, 657–58.

ferent explanation must be forthcoming, for which we offer no solution at present. The problem is one deserving much more detailed study than has been so far bestowed upon it.

SUMMARY AND CONCLUSIONS

The Onondaga formation in Pennsylvania consists of four intergrading, lithologically different, faunally related members. In the east a cherty limestone member overlies the Esopus shale member. In central sections a non-cherty limestone member caps a limy shale member. Locally, the last member may become sandy or carry large proportions of black shale or be represented by a peculiar deposit called "paint ore." The faunas of all members are predominantly Middle Devonian with diagnostic Onondaga species. They are far less closely allied with the Oriskany fauna. Except where local erosion has removed part or all of the formation in central Pennsylvania, the upper contact is transitional with the Marcellus. In every known instance the lower contact with the Oriskany is disconformable.

From these data and by comparison with the Maryland Middle Devonian, with which our sections are most nearly allied, we conclude that the Onondaga formation of Pennsylvania ought to be included with the Hamilton group in the Middle Devonian. This conclusion makes the Hamilton group of Pennsylvania equal to the "Romney formation" of Maryland. We can hardly adopt the designation "formation" here, since the units of our Middle Devonian have been previously shown to coincide closely with the formations of the Hamilton group in New York.[37] Our interpretation is tabulated in Table VII.

In closing, it should be recognized that there is conflicting evidence in New York State as to the nature of the Hamilton-Onondaga contact. Cooper has summed up this situation as follows:[38]

> Following the work of Clarke and Grabau, it has been commonly believed that the Onondaga limestone grades upward into the Marcellus shale (here

[37] G. A. Cooper, "Stratigraphy of the Hamilton Group of Eastern New York," Part I, *Amer. Jour. Sci.*, 5th ser., Vol. XIX (1930), pp. 116–34; Part II, *ibid.*, pp. 214–36 ff.

[38] *Ibid.*, p. 123.

recognized as the basal Hamilton) with the Marcellus overlapping the Onondaga toward the west. Although this interpretation finds some support in the interfingering of Marcellus and Onondaga in Central New York, Chadwick has found evidence of an unconformity between the Onondaga and Marcellus in eastern New York. It is, therefore, possible that there was an interruption in sedimentation at the end of Onondaga time, but it is equally possible that Chadwick's unconformity is actually only a marginal break such as would be expected in the shore region and did not affect sedimentation in the deeper and more distant portions of the geosyncline.

This statement might be applied with equal truth to central Pennsylvania. Evidently, the unconformities in eastern New York are

TABLE VII

Maryland	Central Pennsylvania	Eastern Pennsylvania
Middle Devonian	Middle Devonian	Middle Devonian
Romney formation..	Hamilton group.....	Hamilton group
Hamilton member.	Mahantango formation.	Moscow formation Ludlowville formation Skaneateles formation
Marcellus member.	Marcellus formation...	Marcellus formation
Onondaga member.....	Onondaga formation...	Onondaga formation

analogous to those in central Pennsylvania, which are therefore, as Cooper says, "marginal"; and in general the relations of the Onondaga to the rest of the Hamilton group are transitional.

ACKNOWLEDGMENTS.—The author expresses his appreciation to Dr. Arthur B. Cleaves, of Lafayette College, for his co-operation in contributing data on the Onondaga in Perry County. Further, credit is due Dr. Lawrence Whitcomb, of the Department of Geology at Lehigh University, who has made available a collection of Onondaga fossils from the Lehigh Valley paint ores. These fossils are important, as neither Dr. Kindle nor the writer had access to these mines and as no adequate list of the fauna has appeared. To Dr. Charles Butts the author is indebted for access to his manuscript maps of the Tyrone, Hollidaysburg, and Huntingdon regions, which were helpful in the preparation of Figure 1.

NATURAL BRIDGE AND NATURAL TUNNEL, VIRGINIA[1]

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ABSTRACT

It has long been recognized that Natural Bridge and Natural Tunnel—two of Virginia's most famous natural wonders—are similar in origin. The details of this similarity and the extent of the parallelism in formation have not been fully appreciated. Not until recently has any adequate theory been submitted for the origin of this type of phenomenon. This article discusses the close relation between these two scenic features and suggests a common mode of origin.

NATURAL BRIDGE

Description.—Natural Bridge is located in the southern portion of Rockbridge County, Virginia, 14 miles southwest of Lexington and 39 miles northeast of Roanoke. It is situated in the Valley of Virginia immediately west of the point where James River leaves the valley to break through the Blue Ridge at Balcony Falls. Lee Highway (U.S. No. 11) uses its arch to cross the deep gorge of Cedar Creek, and daily brings many visitors to one of the best-known natural phenomena in the eastern United States.

The bridge is a massive span of limestone, approximately 90 feet long and 100 feet in average width (Fig. 1). It is situated on the northeast slope of a small hill that rises 100 feet above the top of the bridge; the upper surface of the latter slopes to the northeast. The thickness of the arch varies from 40 to 50 feet; and its lower surface is approximately 145 feet above Cedar Creek, which drains the local portion of the valley lowland.

The floor of the Valley of Virginia forms an undulating, but fairly level, lowland that contrasts strongly with the ridges that bound it on two sides. A widespread erosion surface, known as the "Valley-floor (or Harrisburg) peneplain,"[2] is well developed in the Natural Bridge region, where its remnants stand between 1,200 and 1,400

[1] Published with the permission of the state geologist of Virginia.

[2] The writer prefers the spelling "peneplane," which, however, is not the *Journal of Geology* usage.

feet above tide. Some of the streams on this peneplain have developed deep valleys, among them Cedar Creek, which flows beneath the bridge. This stream, one of the active tributaries of James River, rises about 11 miles above its mouth in Short Hills, a monadnock

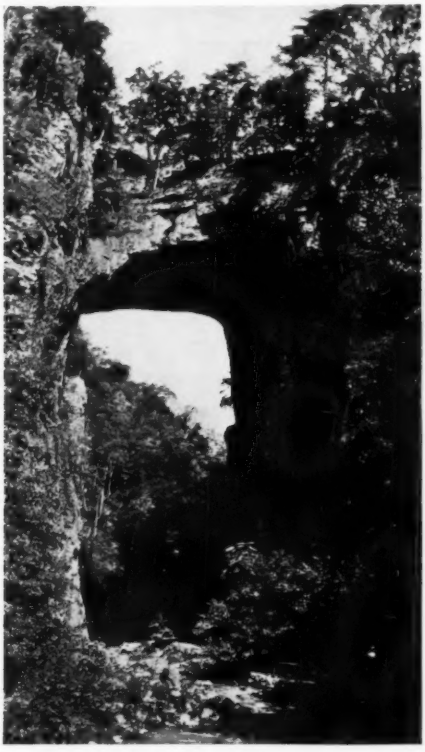

FIG. 1.—Natural Bridge, Virginia, viewed from the southeast

on the Valley-floor peneplain that is capped with Silurian sandstones.

Red Mills, located about 1½ miles northwest of Natural Bridge, is situated at a point that separates the course of Cedar Creek into two distinct portions (Fig. 2). Above Red Mills, the upper portion

of the creek occupies a fairly broad, open valley separated from the adjacent valleys of Broad Creek and Poague Run by low divides, or cols, in each of which are old stream gravels. Both Broad Creek and Poague Run are tributary to Buffalo Creek, which flows into North River to join James River at Balcony Falls, about 8 miles below the mouth of Cedar Creek.

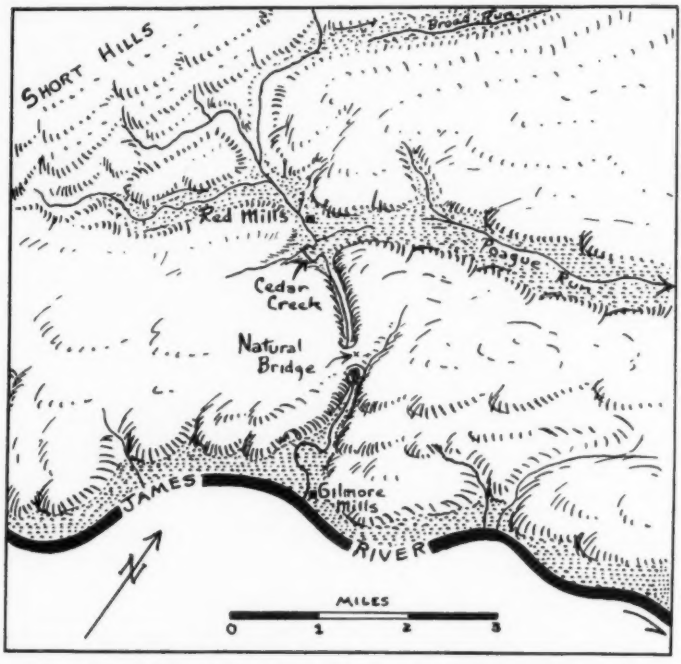

FIG. 2.—Sketch map of the vicinity of Natural Bridge, Virginia. The small tributary entering Cedar Creek immediately below Natural Bridge is Cascade Creek. In this, as in Figure 4, the relief has been somewhat exaggerated to emphasize the physiographic relations.

From a point just below Red Mills to Gilmore Mills at its mouth, Cedar Creek occupies a narrow, steep-sided valley which is more than 3 miles long and 200 feet in average depth, and which becomes gorgelike near the bridge. For 3 miles above Red Mills, the average gradient of the upper portion of Cedar Creek is about 20 feet per

mile; from Red Mills to James River, the gradient is much steeper, averaging 100 feet per mile. Cedar Creek is joined by a small tributary, Cascade Creek, that enters discordantly just below the bridge.

The rocks of the bridge itself, which are limestones and dolomites of the Chepultepec formation of late Cambrian age, are substantially horizontal. Their stratification is readily visible both in the walls of the gorge and in the bridge, where there are many vertical joint planes. A broad, open, synclinal structure, called the "Natural Bridge syncline," is present in this part of the Valley of Virginia. The bridge is located near the southwestern edge of the Chepultepec outcrop along the axis of the fold. As exposed in Cedar Creek both above and below the bridge, the strata are inclined toward this axis. Several small, local faults exist.

Origin.—Thomas Jefferson,[3] in 1794, explained the Natural Bridge as the result of a great "convulsion" of nature. Gilmer,[4] in 1818, described it as the result of solution by underground water, thus correctly explaining the nature of the passage beneath it. Kain,[5] apparently unaware of Gilmer's interpretation, considered it a cave unroofed in all but one place; Ashburner,[6] in 1884, renewed the latter explanation. C. D. Walcott,[7] in 1893, suggested that what is now the bridge was once just above the crest of a former waterfall, and that water seeped below this crest to join the creek beneath the lip of the falls. He postulated that continued enlargement of this opening diverted all of the stream underground and, with subsequent erosion, produced the bridge and its present surroundings. Malott and Schrock,[8] in 1930, advanced a theory that the bridge developed from a meander spur through which water penetrated by

[3] *Notes on the State of Virginia* (Philadelphia, 1794).

[4] F. W. Gilmer, "On the Geological Formation of the Natural Bridge of Virginia," *Trans. Amer. Phil. Soc.*, Vol. I (1818), pp. 187–92.

[5] J. H. Kain, "Mineralogy and Geology of the Northwestern Part of the State of Virginia and Eastern Part of the State of Tennessee," *Amer. Jour. Sci.*, Vol. I (1818), pp. 60–67.

[6] C. A. Ashburner, "Notes on the Natural Bridge of Virginia," *Proc. Amer. Phil. Soc.*, No. 21 (1884), p. 669.

[7] "The Natural Bridge of Virginia," *Natl. Geog. Mag.*, Vol. V (1893), pp. 59–62.

[8] C. A. Malott and R. R. Shrock, "Origin and Development of Natural Bridge, Virginia," *Amer. Jour. Sci.*, 5th ser., Vol. XIX (1930), pp. 257–73.

means of underground channels and through which Cedar Creek ultimately flowed. Wright,[9] in 1934, attempted to reconstruct the later erosional history of the Natural Bridge region, which he thinks involved stream piracy, and suggested that the bridge resulted from the underground diversion of drainage from a higher erosion surface on the west to a lower erosion level on the east, the water entering sinks to reach a lower tributary of James River, which ultimately captured more and more drainage until Cedar Creek was the result.

The writer's theory was formulated during 1931–32, in the course of a survey of the Natural Bridge topographic quadrangle for the Virginia Geological Survey. Although independently formed, it is similar in most of its tenets to the "sink-piracy" theory of Wright, with whom, by correspondence, the writer has discussed both hypotheses and the present paper.

It is here suggested that Cedar Creek is a hybrid, produced by the grafting of portions of two dissimilar and originally distinct drainage basins. The explanation is offered that the waters of present Cedar Creek above Red Mills were at one time tributary to Poague Run, a long eastward-flowing branch of North River. At that time the lower valley of modern Cedar Creek below the bridge was occupied by a small active stream, the precursor of Cascade Creek. Then, Cascade Creek descended rapidly from the Valley-floor peneplain to James River; now, it is a small tributary of present Cedar Creek, which it joins immediately below the bridge. Before the formation of the bridge, however, the Poague Run basin and the drainage of Cascade Creek were separated and distinct.

There are several points to support the interpretation that Poague Run once carried the upper drainage of present Cedar Creek. The col between the two basins now contains gravels of Silurian sandstone, a fact which indicates that it was once occupied by a stream which headed in Silurian rocks: Cedar Creek has such a source. The gradient of the modern branch of upper Cedar Creek valley, if projected across the col into the valley of Poague Run, shows no inconsistencies with the suggested interpretation that the two valleys were once a single basin. At present, the valleys are

[9] F. J. Wright, "The Newer Appalachians of the South, Part I," *Jour. Sci. Lab. Denison Univ.*, Vol. XXIX (1934), pp. 77–101.

linear continuations of each other and are controlled by the same soft rock strata.

Prior to the development of Natural Bridge, Cascade Creek, kept active by its steep gradient, developed a youthful valley in which its headwaters, working northwestward, were considerably below the level of the elongated Poague Run. Although both streams had the same baselevel (James River), Cascade Creek was scarcely 3 miles long, whereas the nearby waters of Poague Run were more than 15 miles from James River. This difference in distance from baselevel enabled the shorter stream to keep its incision more apace with that of the master-stream than its longer rival. Inevitably, a situation arose in which, within a short lateral distance, two different portions of a river system were vying with each other for control of the same local drainage basin. It is suggested that there may have been a difference in elevation of as much as 200 feet between the upper tributary near the present location of Red Mills and Cascade Creek near the site of Natural Bridge.

Given this sharp difference in elevation and a regional dip of the soluble limestones to the southeast, the headwaters of Poague Run had ample opportunity to seek and find a shorter descent to their local baselevel, James River. It is suggested that this descent took place underground, the water sinking into the limestones about $\frac{1}{8}$ mile southeast of Red Mills and emerging into Cascade Creek a short distance below the present site of the bridge.

Possibly this underground course had previously been utilized by drainage; probably it was a well-developed line of weakness in the limestones, transversely crossing the Natural Bridge syncline. Evidences of underground drainage along this line occur in abundance. That a large opening was developed near the supposed entrance of the channel southeast of Red Mills is evinced by unmistakable cave deposits and fluted channels along the east bank of Cedar Creek. "Lost" River, Saltpeter Cave, "Isabella's Staircase," and other cavernous openings exhibited to the visitor lie along this line.

Diversion of the headwaters of Poague Run into the drainage of Cascade Creek gave the latter a greatly increased volume which enabled it to incise its valley much faster than before. Probably this

incision proceeded headward along the underground channel while erosion and weathering began to uncover the roof of the tunnel. No doubt the latter process was already under way even before incision began. As the arch of the tunnel was thicker at its lower end, unroofing would proceed faster and with greater ease at the upper end. The combined effect of incision of the creek bed and weakening and collapse of the tunnel roof would tend to produce a canyon-like gorge, widest in those portions where the unroofing first occurred and narrowest in those portions where the roof remained intact. Disappearance of the remaining elements of the underground channel would leave the span of Natural Bridge as the sole portion of the original roof.

The proposed explanation involves the same agency of underground solution and erosion as do the earlier theories, but the mechanics of the actual bridge formation differ considerably in detail. Its technical difference from the explanation presented by Wright is that it supposes the headwaters of Cedar Creek (then tributary to Poague Run) to have been captured by Cascade Creek, whereas Wright attributes the channel to the underground diversion of drainage (not any particular stream) into an unnamed stream that was gnawing into the eastward-facing escarpment between two adjacent Harrisburg erosion surfaces. The present writer interprets the escarpment as the discordance between two adjacent, but different, portions of the same drainage basin; he is further in doubt as to the course assumed by Wright for the headwaters of Cedar Creek before the formation of the bridge.

NATURAL TUNNEL

Description.—Natural Tunnel is situated in the west-central portion of Scott County, Virginia, 3 miles north of Clinchport and 13 miles northwest of Gate City; it is about 8 miles north of the Virginia-Tennessee boundary line. It is a short distance east of U.S. Highway 23, with which it is connected by a short, privately maintained road. Stock Creek, which enters Clinch River at Clinchport, and the tracks of the Southern Railway pass through the tunnel; a country road makes use of its overhead arch to cross the gorge of Stock Creek.

The tunnel is a cavernous opening at creek level through a spur

of Purchase Ridge. The roof averages 75 feet in height above the creek for the 900 feet of its length. It is considerably higher at the southern end than near the northern end, where the roof is only a few feet above water level. The width of the tunnel averages 130

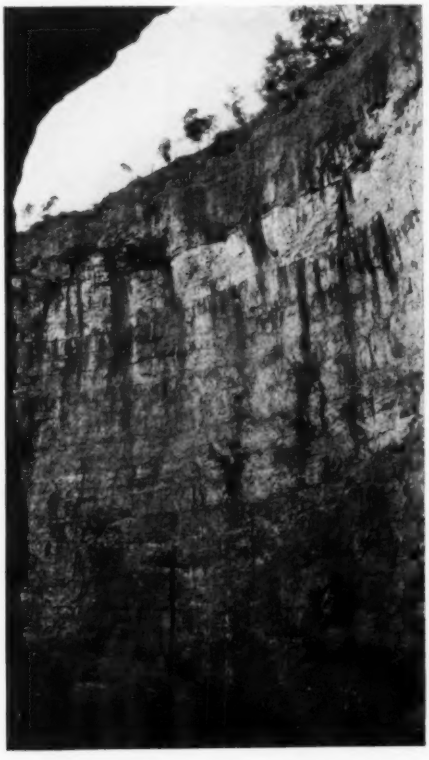

FIG. 3.—The perpendicular walls at the southern end of Natural Tunnel, viewed from the tunnel mouth.

feet, and the passage is gently sinuous. The southern end opens into a spectacular amphitheater, or "crater," formed by the gorge of Stock Creek. The walls of this gorge rise more than 500 feet above the creek and, except for the southern rim, where the creek passes through, are nearly perpendicular (Fig. 3). A similar but less

striking amphitheater occurs around the northern end of the tunnel.

Stock Creek rises along Powell Mountain and flows southward through the tunnel into Clinch River at Clinchport, about 3 miles below Natural Tunnel. The creek is 16 miles long, and its course may be separated into two portions of dissimilar character. The

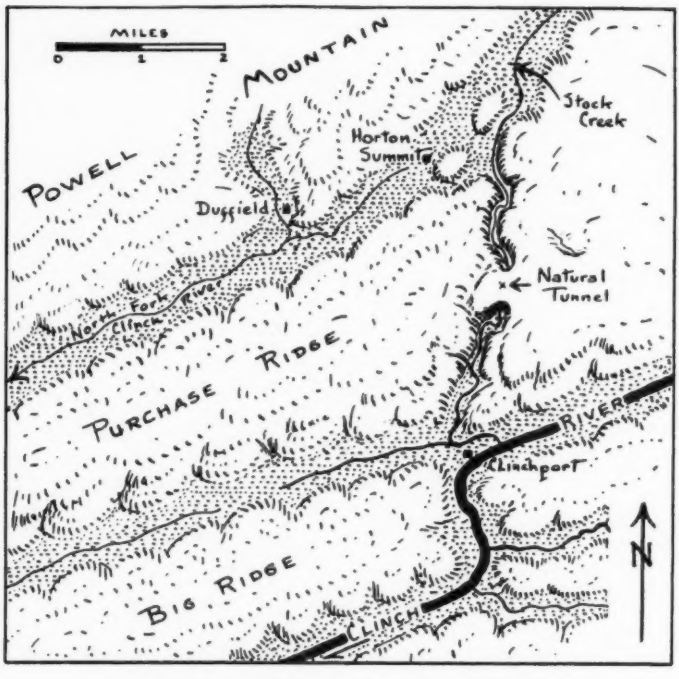

FIG. 4.—Sketch map of the vicinity of Natural Tunnel, Virginia

upper two-thirds occupies a broad subsequent valley which trends southwesterly toward Horton Summit (Sunbright post-office). A short distance above Horton Summit, Stock Creek leaves this open valley to flow due south in a much narrower valley which becomes gorgelike in the vicinity of Natural Tunnel (Fig. 4). The fall of the creek from a point near Horton Summit to Clinch River is about

300 feet in a distance of 6 miles. The tunnel is located at the eastern end of Purchase Ridge, which separates the immediate drainage of Clinch River from that of its chief local tributary, North Fork. The latter joins the main stream in Tennessee, and its chief branch rises in the vicinity of Duffield, which is about 3 miles southwest of Horton Summit. Indeed, the valley occupied by the upper part of Stock Creek and that occupied by the headwaters of North Fork near Horton Summit are continuous; and only a low divide, still capped with stream gravels, separates the two basins.

Natural Tunnel has been eroded in a series of limestones and dolomites. The tunnel itself is in the Copper Ridge formation of late Cambrian age; the cliffs above the tunnel are composed of Nittany dolomite, which overlies the Copper Ridge formation and is of Beekmantown age. The rocks are essentially horizontal at the tunnel and in the cliffs above it, but minor faults and some close folding are evident. The tunnel is located near the southwestern end, and along the axis, of a broad shallow syncline, called the "Rye Cove syncline." The syncline is separated from adjacent structures by thrust faults which strike southwesterly. Upper Stock Creek and North Fork occupy a subsequent valley located along the trace of an overthrust fault. Another fault crosses Stock Creek a short distance above its mouth.

Origin.—Possibly because of its relative seclusion, no attempt has previously been made to offer a detailed explanation of the origin of Natural Tunnel beyond the obvious comment that its manner of formation was similar to that of Natural Bridge. Its origin is commonly attributed to the collapse of a cavern roof. The earliest description of the tunnel was made in 1832 by Long.[10] Other authors have briefly mentioned its analogy to Natural Bridge. The writer emphasizes the remarkable similarity in character and origin between Natural Bridge and Natural Tunnel and proposes the following hypothesis for the origin of the tunnel:

It is suggested that at the time of formation of the Valley-floor (Harrisburg) peneplain, the headwaters of Stock Creek did not flow directly into Clinch River as at present, but followed the rather

[10] S. S. Long, "Description of a Natural Tunnel in Scott Co., Virginia," *Monthly Amer. Jour. Geol. and Nat. Sci.*, Vol. I (1832), pp. 347–55.

wide, open valley past Horton Summit to enter the basin of North Fork of Clinch River. That this open valley still continues from the Stock Creek to the North Fork basin is clear from the present topography; that the present divide was formerly occupied by a stream is evinced by quantities of stream gravel and fluvial débris on the valley floor southwest of Horton Summit. It is a reasonable conclusion that the headwaters of North Fork once extended northeastward to include the upper portion of modern Stock Creek. The lower portion of the course of Stock Creek (below Natural Tunnel) was occupied by a small but vigorous tributary of Clinch River proper, which descended rapidly from the eastern slope of Purchase Ridge to the master-stream.

The floor of the upper valley, then occupied by the elongated North Fork, was at least 300 feet higher than the level of Clinch River at the mouth of the small tributary. This difference in elevation, together with a soluble bedrock, enabled some of the upper drainage to seek underground a shorter route to baselevel. Possibly the water entered sinks that led to previously existing channels, or followed openings that had gradually been developed during the formation of the Valley-floor peneplain. Possibly new channels were formed and enlarged. At any rate, it is suggested that the upper portion of North Fork (now upper Stock Creek) became diverted underground to emerge in the valley of the small tributary of Clinch River. Gradually this transfer became more and more complete, until the headwaters of North Fork became entirely diverted from that stream and engrafted to the smaller tributary of Clinch River proper.

In brief, the theory herein presented for the origin of Natural Tunnel assumes that a tributary of North Fork was diverted through underground channels into a tributary of Clinch River proper, the elongated stream becoming the present Stock Creek. The gorge-like valley of the latter, together with Natural Tunnel, are respectively the eroded walls and last roof remnant of the former underground waterway. Thus the same process assumed for the origin of Natural Bridge is invoked for Natural Tunnel, and the long-recognized similarity between them is made even more apparent.

SUMMARY

Natural Bridge and Natural Tunnel are thought to have approximately the same origin. Each is an arch of limestone which spans a small canyon or deep gorge. In one the arch is narrow, resembling a bridge; in the other the arch is so wide that the passage resembles

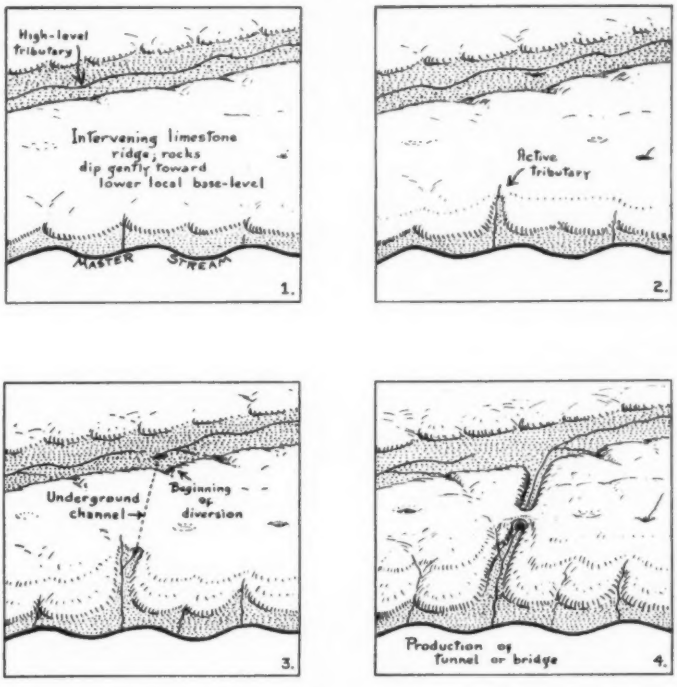

FIG. 5.—Progressive diagrams to illustrate the production of a bridge or tunnel by subsurface piracy.

a tunnel. Each is situated near the axis of a broad shallow syncline, and in both the rocks are nearly horizontal. Approximately the same sedimentary strata are present in both.

The bridge and the tunnel occur on rather small incised tributaries of the master-streams of their region, and the upper portions of

both tributaries occupy valleys that are dissimilar from the lower portions. It is thought that the upper portion of each stream was diverted from an adjacent, but higher, drainage basin through a subterranean passage. In each case, the stream diversion has occurred at a point where the headwaters of a long tributary and the immediate basin of the master-stream are close together and where strong differences in elevation have been responsible for the changes. Soluble limestones, gently inclined from the upper to the lower basins, have furnished lines of underground circulation which first permitted, and later induced, the diversion (Fig. 5).

It is suggested for both features that, after the diversion took place, renewed vigor resulted from the added volume of the streams involved; that incision of the streams occurred; that collapse of the roof of the underground passage commenced; and that similar erosional processes were set in motion which produced the present analogous results. Differences which now exist between Natural Bridge and Natural Tunnel have resulted, it is thought, both from inherent variations in the details of the diversion and from somewhat variant present stages of erosional history. The similarities which occur, however, are far more striking than the points of divergence.

It is highly probable that the production of these analogous features is intimately associated with the development and erosion of the Valley-floor peneplain ("Valley peneplane"[11] and "Harrisburg peneplane,"[12] of Wright), and that there are other relationships than those mentioned which complicate the general picture. It is thought, however, that the interpretation of bridge and tunnel formation, as outlined above, will not need to be essentially altered when these general physiographic relations are more thoroughly studied.

[11] *Va. Geol. Surv. Bull. 11* (1925), p. 27.

[12] *Jour. Sci. Lab. Denison Univ.*, Vol. XXIX (1934), p. 18.

FLOW-UNITS IN BASALT

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ABSTRACT

Basalt flows in the San José Valley, Valencia County, New Mexico, are of pahoehoe type and are characterized by flow-units. A "flow-unit" may be defined as a tongue-shaped structure within a flow. In transverse cross section flow-units are small lenses from 100 to more than 300 feet long and from 10 to more than 20 feet thick. As many as five flow-units, one on top of the other, may occur in a flow. As there is no evidence of erosion, weathering, or deposition between flow-units, the time-interval between them must be short. The simplest flow mechanism for lava is one in which the lava moves as a single unit. The existence of the flow-units, however, indicates a greater complexity in the mechanism of these flows. At the front of the flow and also on its margins tongues a few hundred feet wide break out and flow for considerable distances. A number of tongues form, crusts appear on them, and these tongues are buried by later tongues, which in turn are buried by others. In this way multiple flows are formed. Such flows differ from single flows of pahoehoe type in their greater proportion of vesicles and other cavities, a fact of importance in the movement of solutions through them.

INTRODUCTION

The basalt lava flows of the San José Valley, between Blue Water and the Rio Puerco in Valencia County, New Mexico, have structures the description and interpretation of which shed light on the mechanism of flow. The general shape and extent of these flows are shown on the geologic map of New Mexico by N. H. Darton, published in 1928 by the United States Geological Survey on a scale of 1:500,000. The basalts arrived in place as four separate flows:[1] the Suwanee, the Laguna, the McCartys, and the Blue Water basalts.

The continuity of each of these flows is unmistakable; yet in parts of the Laguna and Suwanee flows numerous outcrops reveal lenses and sheets of basalt, one piled on the other, each of which resembles a separate and distinct flow. However, these lenses and sheets have no great continuity and merge into the main body of the flow. The general field facts indicate that a single flow may in places be multiple and composed of subdivisions that are here called "flow-units." Professor Larsen of Harvard University tells me that he has observed flow-units in basalts in southern Colorado.

[1] Robert L. Nichols, "Quarternary Geology of the San José Valley, N.M.," *Geol. Soc. Amer. Proc. for 1933*, abst., p. 453.

FLOW-UNITS

In transverse cross section flow-units appear as small lenticular bodies from 100 to more than 300 feet long and from 10 to more than 20 feet thick, while in longitudinal section they may be as much as a half a mile long.

These units have been observed and are characteristic of cross sections along more than 8 miles of the Suwanee flow and along

FIG. 1.—A close-fitting contact between two flow-units of the Suwanee flow. The hammer crosses the contact.

more than 7 miles of the Laguna flow and are probably distributed along greater distances of both flows; but detailed vertical sections have been made at only two or three localities.

The two flows which cover the surfaces through which the San José Valley is cut are also of the flow-unit type; and the author believes that, if looked for, such units will be found to be a common feature of basalt flows.

That the contact between flow-units may be so close-fitting that open spaces do not exist is well shown by Figure 1. It suggests very fluid basalt. The figure also shows in a very marked degree the much thinner zone of vesicular lava at the bottom of the upper flow-unit contrasted with the greater thickness at the top of the lower unit. This relationship is a general one. The thickness of the vesicular

zone at the bottom of a unit varies from a few inches to a few feet. One foot is a good figure for the average thickness. The zone of vesicular lava at the top of a unit ranges in thickness from 4 to 10 feet; 6 or 7 feet is a good average. The vesicles are also larger at the top of a flow-unit than at its bottom. The open spaces shown in Figure 1, which are more or less parallel to the contact and as much as 4 feet in length, are probably due to the accumulation of many small gas

FIG. 2.—Contact between flow-units in the Laguna flow. Open spaces common at the contact.

bubbles which were unable to rise farther because of the viscosity of the lava near the surface of the unit. Professor A. C. Lane of Tufts College tells me that he has recognized similar features in the Triassic basalt at Meriden, Connecticut, and also in the Keweenawan basalt of Michigan. The figure shows that columnar jointing is present in the lower flow-unit but is not found in the upper unit; and the wavy outline of the contact indicates that the surface of the lower flow-unit is rough and irregular.

That cavities and open spaces are common, and that the bottom of a flow-unit may be rubbly, all indicating rather viscous lava, is well shown by Figure 2. The greater the liquidity of the flow the closer fitting the contact. The more nearly the flow approaches the aa type the more open is the contact between flow-units. A jointing

parallel to the contact can be seen in the lower unit of Figure 2; and the lava at the contact is red in many places, apparently oxidized by solutions and gases which found easy access along this contact.

Figure 3 is a measured section of the Suwanee flow, while Figure 4 shows flow-units *III* and *IV* of this section. Possibly there are more flow-units at this locality than are shown in the figures, for the bottom of the flow is not seen, owing to a covering of talus and wind-blown sand.

CRITERIA FOR DISTINGUISHING SUCCESSIVE FLOWS

The great lava plateaus in various parts of the world have been built up by a succession of individual flows; the Hawaiian Islands

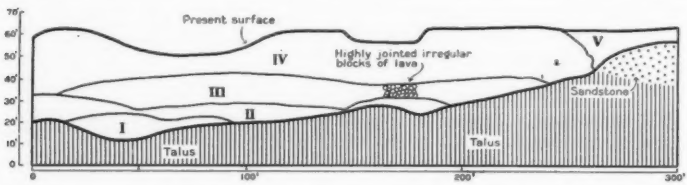

FIG. 3.—A measured section of the Suwanee flow showing five flow-units

owe their origin to the same process; and many occurrences of flow upon flow have been described from many localities. The following criteria have been used to demonstrate that different flows have come to rest successively upon one another: (1) deposition between flows; (2) weathering between flows; (3) erosion between flows; (4) observable contacts; (5) petrography; (6) grain-size studies; (7) distribution of vesicles; (8) columnar jointing; (9) sheeting. All of these criteria cannot be applied in every section. Their relative value varies greatly in individual cases, and it is obvious that combinations of criteria are more to be trusted than any single one of those listed.

CRITERIA FOR DISTINGUISHING FLOW-UNITS

Some of the criteria used for differentiating successive flows are applicable for identifying flow-units; however, certain criteria used to distinguish flow-units can be applied only to them. The following criteria have been used to demonstrate the existence of flow-units: (1) observable contacts; (2) distribution of vesicles; (3) columnar

jointing; (4) sheeting; (5) time-interval between flow-units (there is no weathering, erosion, or deposition between flow-units, as the time-interval between the eruption of units is too short); (6) limited size of flow-units (with successive flows it is often possible to trace individual flows for miles; with flow-units, owing to their limited size, this is impossible); (7) petrography (successive flows may differ petrographically, but flow-units are in general similar petrographi-

FIG. 4.—Shows flow-units *III* and *IV* of Figure 3. Contact between units about halfway down the cliff. Note closely spaced vertical jointing and zone of vesicles at contact.

cally except for differences produced by differential cooling); (8) distribution of grain sizes (that the grain-size of flow-units varies as does the grain size of a single flow is well shown by Figures 5 and 6).

The specimen for Figure 5 was collected at the position marked *1* in flow-unit *IV* of Figure 3, while the specimen for Figure 6 was collected at position *2* in the same unit. The specimen for Figure 5 is a porphyritic glass. The top and bottom of flow-units are characterized by this texture and grain size. The specimen for Figure 6 has a diabasic texture. The center of a flow-unit is in general characterized by this texture and grain size. It is apparent that the grain of Figure 6 is coarser than the grain of Figure 5, and that the augite takes the place of, and crystallized out of, the glass that was once

FIG. 5.—Photomicrograph of a thin section showing basalt with laths of feldspar and either olivine grains or holes which represent olivine grains in a glassy matrix from a specimen collected at the bottom of a flow-unit, Suwanee flow. Magnified 30 diameters.

FIG. 6.—Photomicrograph of a thin section showing basalt with crystals of feldspar and either olivine grains or holes which represent olivine grains in a matrix of augite with a small amount of glass, from specimen collected at the center of the same flow-unit that furnished specimen for Figure 5. Magnified 30 diameters.

present. The variation of grain size in flow-units may be used to identify them in much the same way as it is used to identify successive flows.

TIME-INTERVAL BETWEEN FLOW-UNITS

There is no evidence of weathering or erosion between flow-units, and an inspection of miles of contacts disclosed no sand, gravel, or interbedded material of any kind. However, at one contact in the Suwanee flow, enough time elapsed between flow-units to allow sufficient solidification for the formation of a crack 3 feet deep in the lower unit before the upper unit covered it and filled the crack. In general, however, such filled cracks are rare. Generally the vertical joints of bottom units are unfilled and therefore formed after burial, as is well shown in Figure 1. Collapse depressions, pressure ridges, and squeeze-ups are common on the surfaces of the Laguna and Suwanee flows near their sources but are absent in the areas characterized by flow-units. Moreover, the cross sections of these flows show none of these features at the top of individual flow-units. Their absence from parts of the surface and from all cross sections of the Laguna and Suwanee flows may be due to the fact that the flow-units were too small or lacked through-flowing lava tubes, which may be necessary for their formation. On the other hand, their absence may be due to the short time-interval between the outpouring of units, which did not allow sufficient solidification of the crust to form these features.

Flow-units buried by later units were rigid at the time of burial. No deformation of any kind occurred except the joints produced by cooling. Thin sections of two specimens collected at the bottom of upper flow-units contain a high percentage of glass, indicating that at the time the upper unit came into place it was chilled against the already cold surface of the lower unit. A photomicrograph of one of these thin sections is shown in Figure 5. The dark matrix of the section is glass.

It would seem, then, that the time-interval between units was long enough for a certain degree of cooling and solidification to take place, but not long enough to allow any weathering, erosion, or deposition to occur. All these facts, considered in the light of our knowl-

edge of historic flows, indicate that the time-interval between flow-units is between a fraction of an hour and possibly a day or so.

FLOW MECHANISM OF THE LAGUNA AND SUWANEE FLOWS

The existence of flow-units in the Laguna and Suwanee flows indicates complexity in the flow mechanism. The simplest type of flow is one in which the lava moves as a single unit, somewhat like a flood of water. That the Laguna and Suwanee flows moved in part in this way is indicated by the fact that many cross sections of these flows are massive and structureless. In many places, however, the mechanism of flow was more complicated. The progress of a flow is often not uniform but irregular, owing to the fact that at times the crust acts as an effective dam. With increasing hydrostatic pressure the dam, where the crust is weak, is broken and the lava is free to move. In the cases under consideration, tongues a few hundred feet wide broke out from the front and sides of a flow and flowed on for considerable distances. Crusts appeared on these lava tongues, and solidification proceeded until a degree of rigidity was attained; these tongues were buried by later tongues, which in turn were buried by others.

In Figure 3 each unit represents a single tongue seen in cross section. At the thinnest portion of unit *III* of Figure 3 the lava is highly jointed and rubbly, apparently having moved like aa lava at this point. This was probably due to excessive cooling, conditioned by the thinness of the lava sheet at this place.

Figure 7 illustrates the flow-unit development in plan and in cross section. The diagram indicates that the flow moved mainly as a single unit, although no data were gathered on the relative importance of the single-unit and multiple-unit behavior among the flows studied.

Figure 8 is a block diagram based on a measured section of the Suwanee flow, and shows how a tongue was buried by later sheets of lava.

Dutton,[2] discussing the flow mechanism of the pahoehoe lava of the Hawaiian volcanoes, long ago gave us a clear picture of the flow-unit mechanism.

[2] C. E. Dutton, "Hawaiian Volcanoes," *U.S. Geol. Surv. 4th Ann. Rept.* (1884), p. 96.

The cooling takes place upon the surface of the mass while the interior still remains hot and preserves a viscous liquidity. The superficial crust of cooled lava undergoes rupture at numberless points, and little rivulets of lava are shot out under pressure. Preserving their liquidity for a short time, they spread out very thin and are quickly cooled, forming pahoehoe. Scarcely is one of these little off-shoots of lava cooled when it is overflowed by another and similar one, and this process is repeated over and over again. In a word, pahoehoe is formed by small off-shoots of very hot and highly liquid lava from the main stream driven out laterally or in advance of it in a succession of small belches. These spread out very thin, cool quickly, and attain a stable form before they are covered by succeeding belches of the same sort.

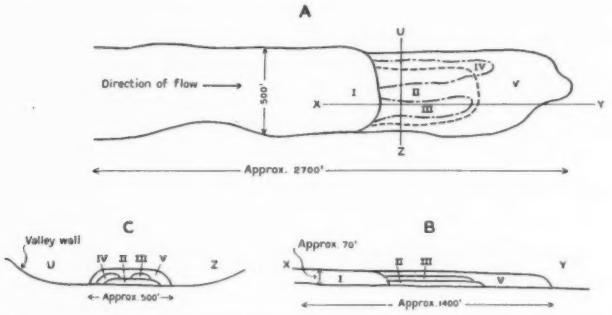

FIG. 7.—Three diagrammatic sketches showing tongues (flow-units) in plan and in transverse and longitudinal section. *A* is the tongues in plan; *B* is a longitudinal cross section along line *xy* of *A*; while *C* is a transverse section along line *uz* of *A*.

Professor L. C. Graton, of Harvard University, informs the writer that he has seen molten slag moving in the same way. Moreover, Lane,[3] by means of drill-core studies, has identified flow-units from the Keweenawan flows of Michigan: "We call these beds, but their irregularity and the similar peculiar trap between each of them show that they are presumably overlapping gushes of the one flow." He has noted two characteristics of flow-units, namely, their limited size and the petrographic similarity of the units.

These lava tongues, being small, would in a short time completely solidify. In the middle portion of the main flow, however, there must be a tube through which all the lava downstream from any

[3] A. C. Lane, "The Keweenawan Series of Michigan," *Mich. Geol. and Biol. Surv. Publ. 6*, "Geol. Ser. 4," Vol. I (1911), p. 320.

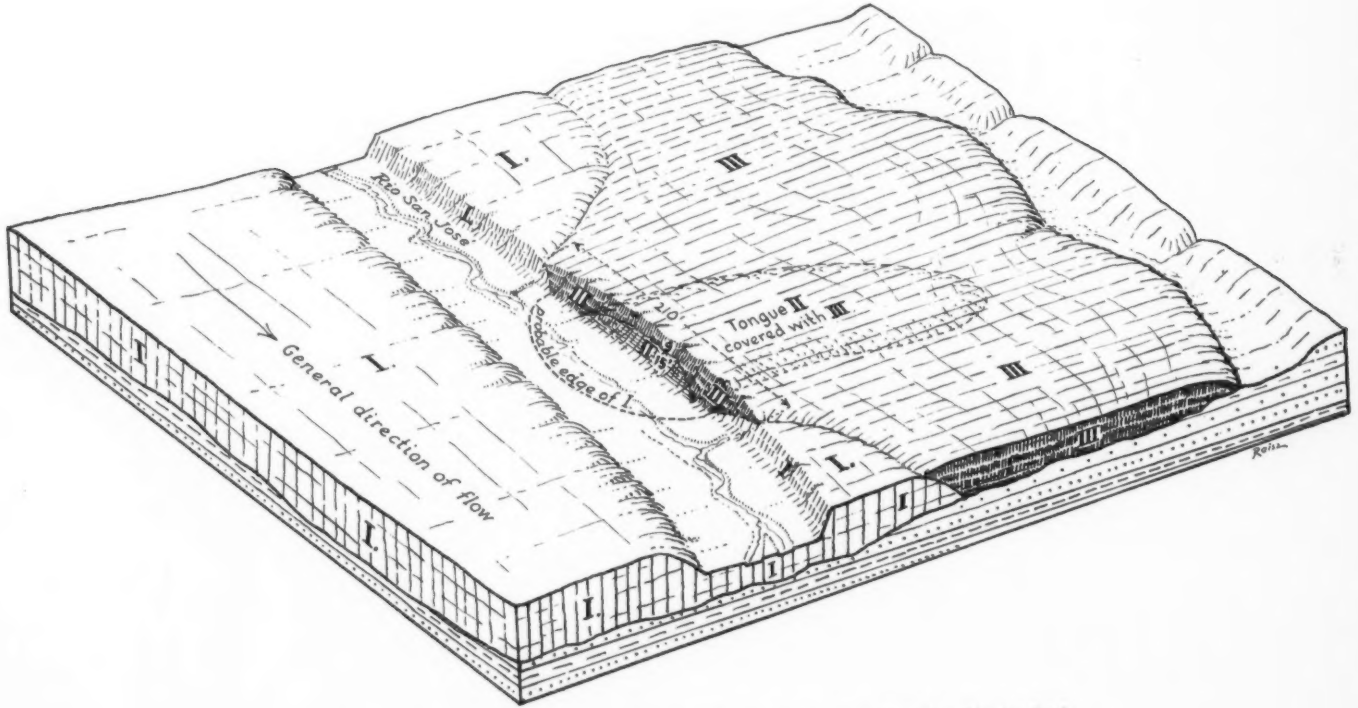

FIG. 8.—Cross section of a buried tongue as seen on the canyon walls of the Rio San José

point can flow. This tube of liquid lava undoubtedly extended down the valley as a continuous single unit. In places it must have rested close to the valley bottom; at other places, on solidified tongues. It might be expected that, in running over a flow-unit, the liquid thread in the tube might cause some remelting; but no evidence of remelting was actually obtained.

Figure 9 is a series of sketches illustrating the method by which the central tube would advance down the valley. The tube would become smaller with increasing distance from the end of the flow, owing to the progressive thickening of the crust. No data were gathered on the diameter of this tube in either the Suwanee or Laguna flows. However, the McCartys flow, which rests on the Laguna flow, must have had a large tube, for the collapse depressions, which are so common on it and which owe their origin to the collapse of the roof of the drained tube, are, in many places, more than 100 feet wide. Moreover, collapse depressions give only a minimum figure for the diameter of their lava tubes, because some of the lava of the tube may solidify in place without draining away. According to Stearns,[4] tubes feeding pahoehoe lava on the Island of Hawaii are as much as 50 feet in diameter.

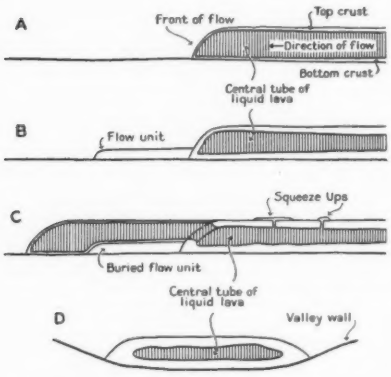

FIG. 9.—Longitudinal and transverse cross sections showing the central molten tube of lava whose motion downstream is the cause of the forward movement of the lava front.

After the lava ceases to issue from the vent, the front of the flow can continue to advance only if the liquid lava in the tube continues to move. Whether the liquid thread drains away or not depends upon the viscosity of the lava and the slope on which it rests. If, however,

[4] H. T. Stearns and W. O. Clark, "Geology and Water Resources of the Kaw District, Hawaii," *U.S. Geol. Surv. Water Supply Paper 616* (1930), p. 108.

the liquid lava in the tube does not drain away, forward motion at the lava front is stopped. Drainage of the tube produces lava tunnels and collapse depressions.

CONDITIONS FAVORING THE FLOW-UNIT MECHANISM

Fluid lava, a steep gradient, and rapid outpouring of the lava—all factors favoring high velocity of flow—favor flow in a single large unit; whereas a more viscous lava, flatter gradient, and slower outwelling of the lava at its source—factors giving lower velocity—favor the development of flow-units. However, under conditions not well understood, a more radical change occurs and aa and not pahoehoe lava results. Variations in the speed of flow produced by the pulsatory nature of the eruption might tend to promote flow by the flow-unit mechanism. Also, in the narrower parts of flows, caused perhaps by topographic restrictions where the velocity of flow would be greater (other things being equal), flow-units would be less common than where flows are wider.

ECONOMIC AND PETROGRAPHIC SIGNIFICANCE OF FLOW-UNITS

That a lava flow may consist not of a single massive unit but of several flow-units has significance for the economic geologist. Cavities and pockets of considerable size may exist at the contacts between flow-units, and each unit has a zone of vesicular lava at its bottom and a larger similar zone at its top. These cavities are potential openings in which water may flow and mineral matter be deposited. Because of the greater abundance of open spaces in multiple flows, it seems reasonable to believe that these flows would form better aquifers and would yield, if mineralized, greater quantities of ore than the single-unit type. Flows in which the liquid thread drained away, leaving collapse depressions and lava tubes, such as those described by Stearns,[5] would be much more favorable for the movement of water or of mineralizing solutions than the type in which this draining did not occur.

The petrographic significance of flow-units is threefold: First, in multiple flows the grain of the rock at any place does not depend

[5] "Volcanism in the Mud Lake Area, Idaho," *Amer. Jour. Sci.*, 5th ser., Vol. XI (1926), p. 359.

upon its distance from the top or bottom of the flow but rather upon its position in the individual flow-unit. Second, the effective thickness through which crystal settling can take place is much less in flow-units than in the average single-unit flow, and therefore examples of gravitational differentiation in flow-unit flows should be less common than in single-unit flows. Third, lava which moves by the flow-unit mechanism in general travels more slowly than lava which moves by the single-unit mechanism. To have both types of flows travel similar distances, it would be necessary that the multiple flow have a greater quantity of superheat or a more effective blanketing of the liquid thread, or both.

ACKNOWLEDGMENTS.—Acknowledgment for help and suggestions is due to Professor Esper S. Larsen, Jr., to Mr. Erwin J. Raisz for the preparation of Figure 8, to Mr. Edward Schmitz for the preparation of Figures 3, 7, and 9, to Mr. F. P. Orchard for photographic help, all of Harvard University; to Professor Melville Munro, of Tufts College, also for photographic help; to Mr. Carlton Chapman and Mr. Marshall Sargent, who assisted the author in the field; and particularly to Professor Kirk Bryan, of Harvard University, at whose suggestion and under whose guidance, both in the field and in the preparation of the manuscript, the work was carried out.

KERN CANYON FAULT,[1] SOUTHERN SIERRA NEVADA

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ABSTRACT

The Kern Canyon fault, described in general terms in two early papers by Professor Lawson, is shown to be an important fault within the southern Sierra Nevada. The scarp is shown to be one of the few known cases of true fault-line scarps. Certain features of the "crustal-rift" hypothesis proposed by Lawson for the region are discussed and shown to be inconsistent with the facts. The peculiar geomorphic discordance of the Kern River with the fault line is pointed out and its significance briefly indicated.

INTRODUCTION

Field work in the Kern River Canyon, carried on in the course of an areal survey of the northern Kernville quadrangle, southern Sierra Nevada, California, has shown that a large fault follows the eastern margin of the canyon from Kernville northward. It is the purpose of this paper to describe some of the important features of the fault and to discuss its characteristics in the 22 miles along which it has been examined in detail.

PREVIOUS GEOLOGIC INVESTIGATION

Apparently no detailed observations of the Kern Canyon fault have been made. In 1902 Lawson made a reconnaissance trip along the canyon of the Kern, from the area south of Kernville to near its headwaters. He published the results in two papers[2] on the geomorphology of the middle and upper parts of the canyon. To interpret the forms in the area studied, several possible hypotheses were discussed, and it was concluded that the placing of a fault in the position suggested by the physiography best fitted the observed and

[1] Not to be confused with the Kern River fault, which crosses the mouth of the Kern River at the point where it enters the San Joaquin Valley. See E. Blackwelder, "Scarp at the Mouth of Kern River Canyon," *Geol. Soc. Amer. Bull. 38* (1927), abst., p. 207.

[2] Andrew C. Lawson, "The Geomorphogeny of the Upper Kern Basin," *Univ. Calif. Dept. Geol. Bull. 3* (1904), pp. 291–376; also, "The Geomorphic Features of the Middle Kern," *Univ. Calif. Dept. Geol. Bull. 4* (1906), pp. 397–409.

inferred facts. Only physiographic evidence for the existence of the fault was presented, however. A paper by W. J. Miller,[3] in 1931, mentions the influence of faulting in the region.

LOCATION AND EXTENT OF THE FAULT

The Kern Canyon fault is a north-south structure located approximately halfway between the eastern and western margins of the Sierra Nevada block (Fig. 1). It parallels closely the marginal faults on the west[4] and the Sierra Nevada fault on the east, and is, so far as the writer is aware, the largest fault within the southern Sierra Nevada that trends parallel to the marginal faults. It is also one of the few faults within the southern part of the range.

The fault is definitely known to extend from Kernville to the mouth of Golden Trout Creek, 40 or more miles to the north. South of Kernville its presence is doubtful, as only weak physiographic evidence for its presence can be found. However, it is possible that it extends as far as the south end of Hot Springs Valley.

EVIDENCES OF THE FAULT

The scarp.—The eastern wall of Kern Canyon for a distance of over 20 miles presents a bold, steep, frayed front, which, although considerably modified by erosion, rises more than 2,500 feet above the trace of the fault and 3,000 feet above the channel of the river. The scarp varies in height, attaining its maximum in the vicinity of Salmon Creek, and dies out northward near the confluence of the Kern and Little Kern rivers. The variable height, and other evidence discussed below, indicate the fault-line character of the scarp.

Discordant profiles of streams crossing the fault.—Profiles of the streams flowing from the eastern block into the Kern show marked gradient changes at the fault line. This is in contrast to the western tributaries of the Kern, whose gradients, although steep, are uniform from head to mouth, even where downcutting of the Kern River has been most rapid.

From the eastern block, the stream with the greatest break in

[3] "Geologic Sections across the Southern Sierra Nevada of California," *Univ. Calif. Dept. Geol. Bull. 20* (1931), pp. 331–60.

[4] Benjamin F. Hake, "Scarps of the Southwestern Sierra Nevada, California," *Geol. Soc. Amer. Bull. 39* (1928), pp. 1017–30.

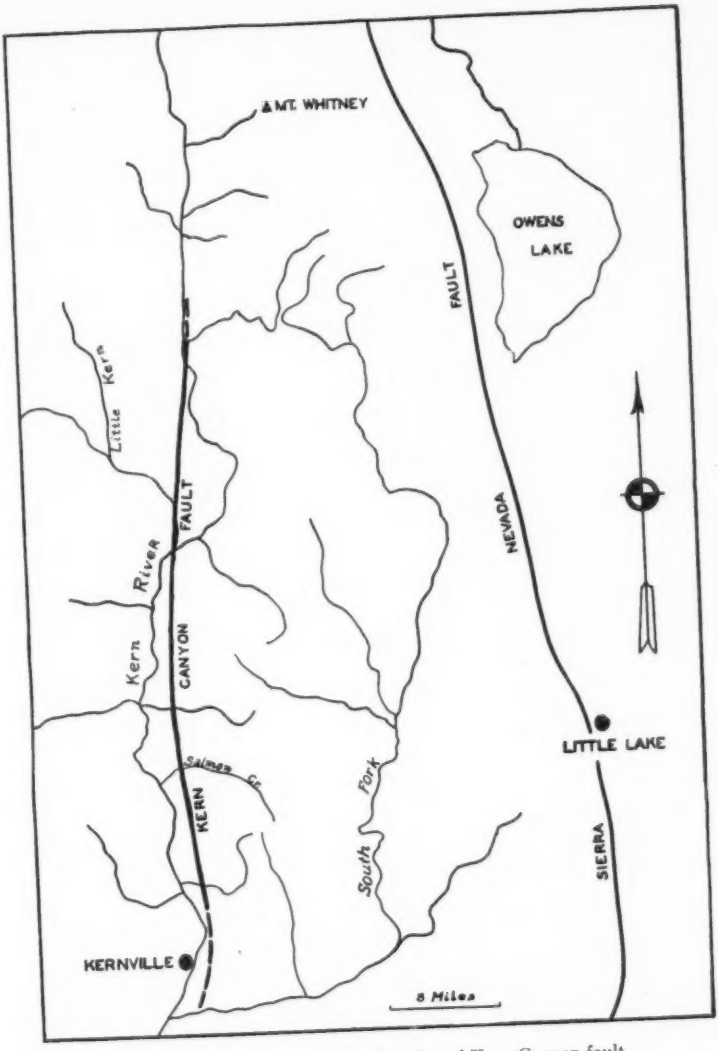

FIG. 1.—Sketch map showing location of Kern Canyon fault

profile is Salmon Creek, one of the longest of the eastern tributaries of the Middle Kern. It heads in a large meadow, 9 miles east of the scarp. From its source to the brink of the scarp its gradient is approximately 100 feet to the mile. In the next mile the gradient changes abruptly to 2,500 feet, while in the last mile to its junction with the Kern the fall is only 400 feet. The abrupt gradient change at the top of the scarp produces a waterfall about 125 feet high and then steep cascades. Cannell Creek, to the south, and Packsaddle Creek, to the north, also show such gradient changes; but they are less pronounced.

These gradient differences are, no doubt, in part due to rock differences along the stream courses. However, tributary streams from both sides of the Kern flow through granitic rocks for the major part of their courses and through metamorphic rocks in their lower courses. Profile breaks occur only in westward-flowing tributaries. Thus a structural difference must account for the convex-concave profiles of the eastern tributary streams.

Line of cols and canyons along the fault line within the canyon of the Kern, with resulting trellis drainage.—As described by Lawson,[5] a line of defiles occurs east of the canyon of the Kern. These are at the base of the scarp and are separated from the Kern River by a median ridge, through which the eastern tributaries flow to reach the river. Small lateral streams of the Kern River tributaries flow north and south along the fault line, producing a rectangular drainage pattern. The alinement of canyons persists along the entire known trace of the fault and is a dominant physiographic anomaly for more than 30 miles northward from Kernville.

Rock difference adjacent to the fault.—The line of the fault marks the boundary between the granodiorite, which makes up 90 per cent of the surface rock of the eastern block, and the more complex crystalline formations (chiefly the Kernville series[6] and associated dioritic and gabbroic intrusives) of the main canyon of the Kern. It should be pointed out, however, that this petrologic relation is not everywhere present, which indicates that an intrusive contact

[5] "The Geomorphic Features of the Middle Kern," *loc. cit.*, p. 405.

[6] Miller, *op. cit.*, p. 335.

cannot be responsible for the physiographic form. Five miles or more south of the junction of the Kern and Little Kern rivers, the Kernville series, which lies against the fault on the west side from Kernville northward, narrows and finally dies out. Its place is taken by granitic rocks, an extension of the granites and granodiorites of the east side, through which the fault passes. Here, as to the south, canyons have been eroded along the fault line.

Discordant attitude between the Kernville series and the fault.—The dip of the beds of the Kernville series one quarter of a mile from the fault is nearly vertical; the strike is N. 45° W., making an angle of 45° with the strike of the fault. At the fault line, however, the deviation of strike is only 10°, and the dip changes from vertical to 45°. This feature is well shown from Salmon Creek northward for 6 or 7 miles. Movement on the fault undoubtedly produced this discordance, probably at the time of formation of the fracture.

Jointing.—Jointing is the dominant minor expression of the fault. In the area near Salmon Creek, where the scarp is best developed, joints parallel the trace of the fault for at least $\frac{1}{4}$ mile on the east, crossing the ridges and canyons of the eroded scarp. Many of these joints show evidence of minor movement. To the south, near Kernville, extensive sheet jointing in granitic rocks and along contacts of the Kernville series and the granitic rocks is parallel to the strike of the fault.

Breccias and mylonites.—Much of the trace is covered by soil and brush. In several places, however, zones of extreme brecciation are found along the fault, grading into complex shear zones and highly altered recrystallized rocks.

Warm springs.—At several places along the fault, especially just north and south of Kernville, warm springs emerge from sheared zones, particularly in granitic rocks, and also from alluvium covering the projected trace of the fault.

Activity of solution.—Near the fault, in areas of marble within the Kernville series, are found marble caves of considerable size and coarse limestone breccias. It is thought that the caverns are the result of solution by waters migrating upward through channels and fissures along the fault. Marble areas at a distance from the fault do not show these characteristics.

CHARACTER OF THE SCARP

From Kernville northward for more than 20 miles is developed the highest scarp to be seen along the known trace of the fault. The following evidence[7] shows that this scarp is a fault-line scarp: (1) The height of the escarpment varies from place to place along the trace of the fault. (2) The scarp occurs throughout its length on the same side of the fault, but it has its greatest height where weak rocks are present on the lower side of the escarpment. (3) To the north, at the point of confluence of the Kern River with the Little Kern (Fig. 1), a series of lava flows covers the trace of the fault. These flows are not the most recent of the later volcanic rocks of the southern Sierra; they may be Pliocene in age. They are not broken by the fault; and prior to the extrusion of the lava, the fault trace was beveled, so that the lavas lie on an old land surface. (4) The corresponding elevation of surfaces on the two sides of the fault south of the junction of the Kern and Little Kern rivers indicates that no movement has taken place since the fault line was beveled. (5) There is no evidence of recent movement anywhere along the fault. Thus, the evidence proves that the face rising from the trace of the fault is a fault-line scarp.

DISPLACEMENTS ALONG THE FAULT

There has been no postlava activity along the fault. In extensive petrologic and areal studies within the Kernville quadrangle, the writer has discovered no evidence from which the nature of the movement on the fault might be ascertained. The change in attitude of the Kernville series as the beds approach the fault, as discussed above, may be an indication of the character of movement, but it is not sufficiently definite to lead to any conclusions.

RIFT VERSUS FAULT LINE

Lawson[8] has suggested that a crustal rift, along the line of the Kern Canyon fault, has determined the course of the Kern River. The

[7] The validity of evidence in favor of the fault-line character of scarps and the criteria for their recognition have been discussed by E. Blackwelder, *Jour. Geol.*, Vol. XXXVI (1928), pp. 289–311.

[8] "The Geomorphology of the Upper Kern Basin," *loc. cit.*, pp. 336, 365; "The Geomorphic Features of the Middle Kern," *loc. cit.*, p. 409.

writer's analysis of the evidence suggested by Lawson affords no support for this hypothesis. Observations extending along the entire known trace show that it is confined very closely to the line of defiles within the canyon and east of the Kern River itself, and no evidence has been uncovered which would suggest the existence of more than one fault along this line. Examination along most of its length, and for several miles on either side, has brought to light no indication of a second fault, complementary to the Kern Canyon fault, on the west side of the canyon. Dr. Matthes, who is engaged in studies in the Sequoia National Park region, informed the writer[9] that he has been unable to find evidence of "rifting" on the Upper Kern, where the rifting hypothesis was first applied by Lawson.[10]

LACK OF COINCIDENCE OF THE KERN RIVER AND THE FAULT LINE

Examination of the sketch map (Fig. 1) shows at once that the course of the Kern River and the trace of the fault do not coincide except for short distances.

The explanation is found in the complex series of events which produced the present physiographic features. The Kern River is a superimposed stream, incised as a result of rejuvenation following the development of the old land surfaces on which the Pliocene (?) volcanics were extruded. At that time, the line of the fault had no physiographic expression in the area where it is crossed by the Kern, the fault having been planed in the development of the old land surface. Although positive evidence has long since been erased, the initial southward-flowing course of the Kern may have been determined by the fault in an earlier cycle. The present physiographic expression of the fault is due entirely to exhumation of the fault line during the present cycle.

SUMMARY

It thus appears that the Kern Canyon fault exists as a major structural feature with geomorphic expression in the present southern Sierra Nevada. The fault is approximately parallel to the Sierran marginal faults. The fault-line character of the scarp is

[9] Personal communication.

[10] "The Geomorphology of the Upper Kern Basin," *loc. cit.*, p. 342.

proved by (1) the varied height of the scarp, (2) the presence of the highest scarp where weak rocks occur on the lower side, and (3) the ancient date (pre-Pliocene ?) of movement on the fault. The fault is a single continuous fracture or very narrow fault zone, and is not a crustal rift. Finally, the geomorphic discordance of the Kern River with the fault line is explained.

ACKNOWLEDGMENTS.—In conclusion, the writer wishes to thank Professor W. J. Miller, of the University of California at Los Angeles, for the suggestion of the problem; Professor J. P. Buwalda, of the California Institute of Technology, and Dr. Catherine Campbell, for criticism of the manuscript; and Mr. Robert P. Bryson, graduate student of the California Institute, for assistance in the field studies.

DEVONIAN ROCKS IN THE BIG SNOWY MOUNTAINS, MONTANA[1]

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ABSTRACT

Calvert and Reeves have reported that Mississippian limestones rest directly upon Cambrian rocks, and that Devonian sediments are absent in the Big Snowy Mountains. In connection with a recent field investigation near Half Moon Pass, approximately 250 feet of Devonian limestones and dolomites were found resting upon an eroded surface of Upper Cambrian shales and limestones. These Devonian rocks contain poorly preserved corals (*Favosites?* and *Pachyphyllum*), brachiopods (*Athyris, Atrypa,* and *Spirifer*), and hydrozoans (*Stromatopora*), and are overlain by 2 feet of limestone and black, fissile, conodont-bearing shale. The Devonian limestones in the Big Snowy Mountains are tentatively correlated with the Upper Devonian Three Forks shale.

Throughout the Rocky Mountains of western Montana, Upper or Middle Cambrian sediments are overlain by Middle and Upper Devonian rocks[2] called the "Jefferson formation" by Peale.[3] These Devonian limestones are overlain by Mississippian rocks, also named by Peale,[4] the "Madison limestone."

The writer measured seventeen sections of Paleozoic rocks in northwestern Montana during 1932 and 1933, and, in that connection, examined the literature of the subject for the entire state. That study disclosed the fact that the only Paleozoic section in western and central Montana in which Devonian rocks were reported to be absent is in the Big Snowy Mountains.[5] Because the Jefferson formation is well developed and relatively uniform in thickness throughout the state, and particularly in the Little Belt Mountains, the reported absence of Devonian rocks in the Big Snowies, only

[1] Published with the permission of the director of the Montana State Bureau of Mines and Geology.

[2] The Big Horn dolomite (Ordovician) occurs only in the Big Horn, Pryor, and Beartooth ranges in the southern part of Montana.

[3] A. C. Peale, "The Paleozoic Section in the Vicinity of Three Forks, Montana," *U.S. Geol. Surv. Bull. 110* (1893), p. 27.

[4] *Ibid.*, pp. 33–39.

[5] W. R. Calvert, unpublished manuscript quoted by C. D. Walcott, "Relations between the Cambrian and Pre-Cambrian Formations in the Vicinity of Helena, Montana," *Smithsonian Misc. Coll.*, Vol. LXIV, No. 4 (1916), pp. 274–76.

30 miles to the west, seemed very improbable. Similar anomalies in the Cambrian section of these mountains, such as Calvert's figure of 750 feet of Wolsey shale, and the reported absence also of Upper Cambrian sediments[6] appeared likewise doubtful, because the Wolsey averages only 240 feet in thickness elsewhere in Montana, and the Upper Cambrian rocks thicken eastward in all of the other sections in central and western Montana. In 1935, during a revision of the Cambrian type sections and formations of Montana and Yellowstone National Park, it became necessary to remeasure the Half Moon Pass section in the Big Snowy Mountains and to examine the overlying Paleozoic rocks in contact with the highest Cambrian beds. The opportunity was thus afforded to study hastily the Devonian and Lower Mississippian rocks.

The Big Snowy Mountains are an isolated range near the center of Montana, and are composed largely of Paleozoic sediments which are overlain near the periphery of the range by Mesozoic shales and sandstones. The basal Cambrian sandstone rests almost conformably upon Beltian shales and argillites of the Greyson formation. The structure of the mountain mass is a simple asymmetrical anticline, the south limb of which dips more steeply than the northern one.[7] The apex of the structure is three-quarters of a mile south of Half Moon Pass, near the eastern third of the range and at the head of Swimming Woman Creek. At this place erosion has exposed approximately 300 feet of Beltian shale. The Paleozoic section is largely exposed, and consists of Middle and Upper Cambrian, Upper Devonian, and Lower Mississippian sediments. The part of this section pertinent to the present discussion may now be summarized (Fig. 1).

The top of the Cambrian section is composed of 32 feet of maroon, olive-green, and gray fissile shales, massive argillaceous limestones, and hard, crystalline, intraformational conglomerates. These beds contain Upper Cambrian trilobites and are tentatively correlated with the Dry Creek shale instead of the Meagher limestone of the Little Belt Mountains. The upper part of the Cambrian rocks is eroded to depths of 3 feet within horizontal distances of 50 feet or

[6] Calvert, *ibid.*, pp. 274–75.

[7] For maps and structure of the Big Snowy Mountains see Frank Reeves, "Geology of the Big Snowy Mountains," *U.S. Geol. Surv. Prof. Paper 165-D* (1931), Pls. 37–38.

less (Fig. 2). Overlying the Dry Creek shale disconformably are 250 feet of thick- and thin-bedded, gray, buff, and chocolate-gray, argillaceous, generally dolomitic, petroliferous Devonian limestones which are strikingly different in composition and appearance from the subjacent Cambrian and superjacent Mississippian beds (Fig. 3). Within a zone 20–35 feet below the top of these Devonian rocks occur poorly preserved corals (*Pachyphyllum*, similar to *P. woodmani* [White] and doubtful *Favosites*); brachiopods (*Athyris*, *Atrypa*, and

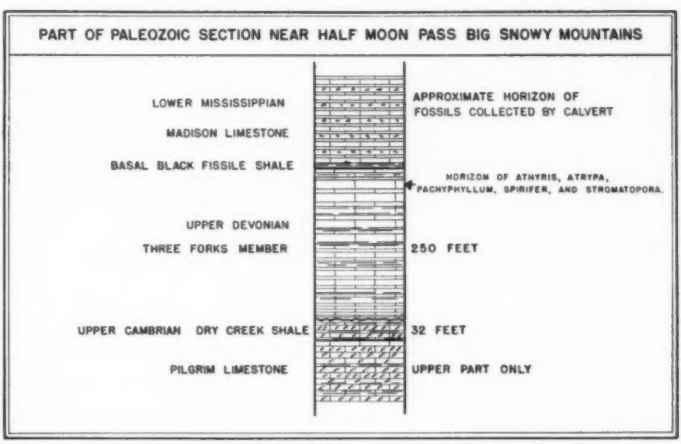
PART OF PALEOZOIC SECTION NEAR HALF MOON PASS BIG SNOWY MOUNTAINS
LOWER MISSISSIPPIAN
MADISON LIMESTONE
BASAL BLACK FISSILE SHALE
UPPER DEVONIAN
THREE FORKS MEMBER
UPPER CAMBRIAN DRY CREEK SHALE
PILGRIM LIMESTONE
APPROXIMATE HORIZON OF FOSSILS COLLECTED BY CALVERT
HORIZON OF ATHYRIS, ATRYPA, PACHYPHYLLUM, SPIRIFER, AND STROMATOPORA
250 FEET
32 FEET
UPPER PART ONLY

FIG. 1.—Part of Paleozoic section near Half Moon Pass, Big Snowy Mountains

Spirifer); and hydrozoans (*Stromatopora*). The upper boundary of the Devonian beds is marked by a zone 2–3 feet in thickness of black fissile conodont-bearing shale and limestone, which forms the basal part of the Mississippian Madison limestone. The Madison above this basal zone consists largely of gray, thick- and thin-bedded, crystalline limestone containing irregularly disseminated dark chert nodules. These beds also contain large numbers of brachiopods, corals, and bryozoans characteristic of the Madison everywhere in the Cordilleran geosyncline.

In his original description of the upper part of the Cambrian and the lower part of the Madison at Half Moon Pass, Calvert said:

> Overlying the Wolsey shale is a formation with very distinct and characteristic lithology. It is composed of layers of firmly cemented, flat, limestone

FIG. 2.—Erosional disconformity between Devonian limestone and Cambrian shale exposed in cliffs on south side of Greathouse Peak, west of Half Moon Pass.

FIG. 3.—Relationships of Mississippian (Madison limestone), Devonian (Three Forks limestone), and Cambrian (Dry Creek and Pilgrim formations) exposed in cliffs on south side of Greathouse Peak, west of Half Moon Pass.

pebbles, with thin partings of gray fissile shale. . . . . From the lithology and the relation to the underlying Wolsey shale this conglomerate is correlated with the Meagher limestone, described by Weed in the Little Belt Mountains folio. . . . . Overlying the Meagher limestone is a thick mass of calcareous strata (the Madison limestone) that constitutes the bulk of the Big Snowy Mountains. This mass may be separated into three distinct lithologic units. The lowermost comprises 200 feet of chocolate-colored limestone, cherty throughout and massive in general appearance, though in reality somewhat thinly bedded. A striking characteristic in connection with this limestone is the strongly fetid odor emanating when struck with a hammer, due no doubt to some form of sulphur. It was supposed in the field that this limestone corresponds to one of similar character in the Little Belt Mountains, assigned by Weed to the Siluro-Devonian. In the Half Moon Pass locality, however, the writer collected fossils from the limestone, near the top to be sure, but from a zone similar in every respect to the strata between that zone and the Meagher limestone. According to Dr. Girty who made the identifications, this collection contained *Pinnatopara* sp., *Spirifer centronatus*, and several species of *Fenestella*, referred by him to the Madison limestone of Mississippian age.[8]

The fossils collected by Calvert are Madison in age, but the horizon from which they were obtained is near the top of Greathouse Peak, a hundred or more feet above the top of the black, conodont-bearing shale at the base of the Madison limestone. Calvert's description of the lower part of the Madison limestone is partly correct for that formation in the Big Snowy Mountains, but is incorrect for the underlying 250 feet of Devonian strata, because these Devonian limestones are dolomitic, are gray and buff-gray, weathering distinctly lighter gray than the overlying Mississippian limestones, and do not contain dark cherts.

The conclusion which is forced upon one by the fact that Calvert did not describe the characteristics of the Devonian rocks is that he did not see them and therefore left a gap in his section.

In 1931, Reeves described the higher Cambrian and Lower Mississippian beds at Half Moon Pass, and followed Calvert's practice. Reeves said:

Underlying the Quadrant formation with apparent conformity is the Madison limestone, of lower Mississippian age. . . . . The lower part of the formation is composed of thin bedded gray to brown limestone, some beds of which are petroliferous. . . . . The formation is very fossiliferous, especially in its lower thin bedded part. No fossil collections were made in the formation except two

[8] Calvert, *op. cit.*, pp. 275–76.

from the thin bedded limestone which Calvert regarded as comprising the basal part of the Madison limestone but which is similar in both lithology and stratigraphic position to beds in the Little Belt Mountains classed by Weed as Silurian and Devonian. According to G. H. Girty who identified these fossils, they are of Madison limestone age and confirm Calvert's conclusion that there are no beds in the Big Snowy Mountains between the Madison limestone and the Meagher limestone, of Cambrian age.[9]

The lower part of the Madison limestone is rich in fossils; but, as previously pointed out, their horizon is several hundred feet above the Cambrian, and more than a hundred feet above the black, conodont-bearing shale at the base of the Madison itself. Further, Reeve's description of the Madison, like that of Calvert, is correct but does not apply to the beds containing Devonian fossils or to the buff and gray dolomites between these fossil-bearing beds and the top of the Cambrian.

Two points become clear: first, the fossils which Girty identified were undoubtedly from the Madison limestone; and, second, Calvert and Reeves recognized neither the division line between the Mississippian and Devonian nor the disconformity between the Devonian and Cambrian rocks in the Big Snowy Mountains. In any event, it can now be certainly stated that approximately 250 feet of Devonian limestones and dolomites are present in the Big Snowies; are overlain by Lower Mississippian black fissile shale and cherty crystalline limestones; rest disconformably upon Upper Cambrian shales, limestones, and intraformational conglomerates (Fig. 1); and that these Devonian strata contain poorly preserved corals (*Pachyphyllum* and doubtful *Favosites*), brachiopods (*Athyris*, *Atrypa*, and *Spirifer*), and hydrozoans (*Stromatopora*). Drs. G. A. Cooper and Edwin Kirk, of the United States National Museum, kindly examined the specimens and tentatively consider them to be Upper Devonian in age. If this conclusion is correct, the Devonian limestones in the Big Snowy Mountains should be correlated with the Three Forks shale, and not with the Jefferson limestone. The discovery of these Devonian sediments adds considerably to our knowledge of the Paleozoic section in these mountains, and establishes a new Devonian section in an area isolated from the other published sections containing rocks of this period in Montana.

[9] *Op. cit.*, pp. 143–44.

A NOTE ON CHINK-FACETED PEBBLES

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In 1925 the writer described chink-faceted pebbles, formed in marine boulder beaches at a number of localities in Hawaii. More recently the writer, as well as H. S. Palmer, has found such pebbles at various points on the coasts of Oahu and Hawaii. It is the writer's impression, supported by that of Palmer,[1] that they rarely occur in the typical forms found at the type localities on the coasts of Molokai and Lanai, though less mature examples can be found more widely.

In the paper mentioned, it was concluded that, "while it is possible that conditions favoring this process may in rare instances be found in streams, it seems on analysis far less likely that they will be. . . . . From consideration of the points enumerated it will appear that chink-faceted pebbles may practically be considered as exclusively of marine or lacustrine origin."[2]

This theoretical conclusion must now be replaced by the fact that chink-faceted pebbles, indistinguishable from the marine variety, have been found in stream channels near Honolulu. Data are insufficient for generalization; but the localities so far found are in the rugged mountain sections, where large boulders are lodged in semi-permanent positions and where water in wet seasons and after storms passes down among them so as to impart a slight, oft-repeated motion to smaller rock fragments. It is difficult to make any estimate of the relative abundance of fluvial and marine chink-faceted pebbles, but the marine variety probably is much more abundant. It is believed that marine chink-faceted pebbles are commonly cut from hard basalt exposed by strong erosion, whereas the fluvial type is more commonly cut from weaker, weathered basalt in the upper stream channels.

[1] H. S. Palmer, personal communication.

[2] C. K. Wentworth, "Chink-faceting: A New Process of Pebble-shaping," *Jour. Geol.*, Vol. XXXIII (1925), p. 267.

REVIEWS

Erdölmuttersubstanz. A symposium of seven papers by eight authors edited by OTTO STUTZER. ("Schriften aus dem Gebiet der Brennstoffgeologie," Heft 10.) Stuttgart: F. Enke, 1935. Pp. vi+181; figs. 25. RM. 17.00 (paper covers).

E. Wasmund: "Subaqueous Formation of Anabituminous Adipocere," 70 pages.

K. Krejci-Graf: "On the Formation of Bituminous Sediments," 24 pages.

F. Hecht: "Fundamentals of Chemical Fossilization," 26 pages.

A. Treibs: "Vegetable Matter as Source Materials of Petroleum," 28 pages.

R. Potonié and D. Reunert: "Geochemical Studies of Sapropels from Two Lakes," 21 pages.

H. Steinbrecher: "Absence of Higher Temperatures during Origin of Petroleums," 5 pages.

D. Wolansky: "Petroleum Source Materials and Their Conversion as Seen by Russian Geologists," 7 pages.

Wasmund, geologist and limnologist, considers that adipocere forms not only from fatty materials, but also through anaerobic action on albumins. His work is based on vertebrate remains, including man; no evidence for similar results from invertebrates is presented. Krejci-Graf, geologist, emphasizes the conclusion that source rocks are of marine origin and probably rich in organic matter. Hecht, micropaleontologist, discusses alteration of marine animal matter, and regards excrement as an important source of bitumen. Treibs, organic chemist, discusses Hackford's and Berl's studies, and describes his spectroscopic evidence that petroleum carries porphyrins derived from chlorophyl and to a lesser extent from blood, thus precluding temperatures over 200° C. during petroleum genesis. He emphasizes that not fats alone, but carbohydrates and albumins must also be regarded as important source materials. The absence of chlorophyl-porphyrins in peat shows how readily these are destroyed by exposure to the air. Potonié and Reunert, geologists, give detailed descriptions of techniques and results. They conclude that researches on marine sediments have not yet demonstrated these to be potential source materials, and consider that in some respects the lake deposits studied may be regarded as source rocks in the making. Steinbrecher, lignite chemist, shows that petroleums carry materials that

would be destroyed by higher temperatures. Miss Wolansky's paper is a summary of the work of Archangelski, Kalitzki, and Orlov. The latter two regard eel grass and algae, respectively, as source materials.

Numerous references are cited; an Index is lacking.

D. JEROME FISHER

Problems of Petroleum Geology: A Sequel to *Structure of Typical American Oilfields*. A symposium of forty-three papers by forty-seven authors edited by W. E. WRATHER and F. H. LAHEE. Tulsa: Amer. Assoc. Petroleum Geologists, 1934. Pp. xii+1073; figs. 187; pls. 6. $6.00.

This volume and the two preceding ones were prepared under the personal supervision of Sidney Powers. His death late in 1932 left the final editing of this symposium to others, who dedicate it to his memory.

The papers are classified into seven divisions as follows:

Division	Subject	Number of Papers	Pages
1	History of the structure theory	1	24
2	*a*) Source beds, source matter, micro-organic action	3	42
	b) Carbon ratio theory	1	30
	c) Evolution of petroleums in four U.S. provinces (omitting the Mid-Continent), hydrogenation	5	150
3	Origin, migration, accumulation (general papers)	7	182
4	Origin, migration, accumulation in terms of various regions of the U.S.	16	378
5	Compaction, reservoir strata	2	26
6	Oil-field waters of the five U.S. provinces	7	154
7	Geothermal gradients	1	36

A thorough fifty-one–page Index completes the work.

To describe the volume tersely, it may be likened to an advanced textbook emphasizing the theoretical subject of the origin of petroleum. It differs from what such a manual should be in that it is necessarily incomplete in certain aspects from this point of view, is practically limited to a consideration of conditions in the United States, and is inconsistent. The latter condition follows from the treatment by many authors of a controversial subject and is in at least some respects a virtue (Shakespeare to the contrary) because of the present state of limited knowledge but

extensive literature of the subject. The volume has the strong qualities of being, in general, authoritative and stimulating. It will likely disappoint those who mistakenly hope for a rounded, well-supported picture. Although perhaps confusing to the tyro, it is indispensable to the more advanced worker seriously interested in any phase of the geology of petroleum. Because of the very unfortunate delay in the appearance of this review, detailed discussion of the various papers is out of order. Suffice to say that a large proportion of them consists of outstanding contributions.

D. JEROME FISHER

The Snellius Expedition in the Eastern Part of the Netherlands East Indies 1929–1930, Vol. V: *Geological Results*, Part I: *Geological Interpretation of the Bathymetrical Results*. By P. H. KUENEN. Utrecht: Kemink en Zoon N.V., 1935. Pp. 124; figs. 47; pls. 9.

Although the title might not lead one to suspect it, this report is a major contribution to tectonic geology. The results, based on some thirty thousand new echo soundings, and the masterly treatment of their tectonic implications are of extraordinary interest and great value. Light is thrown on so many different debated questions within these few pages that the report itself must be read to appreciate the importance of its contributions. A brief review cannot cover them. The discussions are concise but nevertheless rather easily read, considering their scope and the inherently difficult nature of the problems.

The reviewer perhaps cannot do better than to quote a few selected sentences. Some of the recognized fault scarps

> demonstrate the ability of a fault to reach gigantic proportions without the aid of erosional obliteration of the load of the thrown-up limb. . . . . Examples are given from the middle of the Indian Ocean, from a position where we may safely claim to be in the heart of the sima exposure. The plastic nature of the sima, as claimed by Wegener and others, is not borne out by this characteristic.

The relief of the sea floor was found to be of the same order of magnitude as that of the land surface, discounting the erosion on land, though the charts do not show individual anticlines and synclines comparable to those of most folded areas on the continents. This was partly because the soundings were mostly taken too far apart to reveal these smaller forms. "The general impression to be gained from the chart is that the major forms, at least, are bent gradually and evenly; therefore, that faulting is not the principal cause of the relief." However, "the straits between the adjacent islands on a geanticline in localities where the rows of islands and

the geanticline form a straight or only a slightly curved line must be explained by faulting."

The principal orogenic episode in the East Indies occurred in the Miocene, but the results of this expedition indicate that the deep-sea troughs and geanticlines date from the end of the Tertiary and are still in course of further development.

The excellent discussion of the relation of the East Indian deep-sea basins to ancient geosynclines should be read carefully.

> In summing up the tentative results, we find that neither the position of a geosyncline with relation to continents, nor the depths are quite satisfying properties for a genetic classification. . . . . Although at present faults frequently bound the geosynclines, on closer examination they appear to have been formed during a later stage and not during the subsidence of the trough. . . . . In our quest for modern equivalents we may assume that the troughs having a faulted nature are not representatives of the *normal* type. . . . . So far as our present knowledge goes, we are justified in regarding the Timor Trough as a modern geosyncline in act of formation.

Kuenen is of the opinion that the Alps and East Indies are sufficiently alike to justify the belief that in the latter region we are witnessing the earlier stages of a mountain-building cycle. "The alpine structure teaches us what the East Indian sub-structure is like, and the East Indies illustrate a former stage of the alpine orogenesis." Consequently geologists who are studying older orogenic belts may find the solution of some of their stratigraphic and structural problems by a comparison with the East Indies.

Considerable attention is given to the sliding of layers of sediment in this region of marked submarine relief. The evidence appears to indicate that sliding plays only a subordinate part in the sedimentation which takes place in the deeper parts of the troughs. The author concludes that

> either the theory of sliding must be abandoned as the principal cause of mountain folding, or the east part of the East Indies is not at present a region of tectonic activity . . . . there still remain the more general objections based upon differences between structures caused by compression and those which would result from sliding, for these were all in favor of tangential compression.

New evidence indicates that the Australian continental block is delineated by the 500-meter line in a manner quite different from what has been believed heretofore. A discussion of the implications of this discovery is summed up as follows:

> The new chart has given several convincing indications that the shape of the Outer Banda Arc cannot be the outcome of relative differences in horizontal

movements in an arc's endeavor to adapt itself to the shape of the Australian continental block.

The author discusses in succession the tectonic theories of Stille, Brouwer, Lawson, Lake, Ruud, Hobbs, Staub, Van Bemmelen, Wegener, and Smit Sibinga as they have been applied or may apply to these island arcs. All apparently encounter difficulties and serious objections. "The drift theory, as applied to the East Indies by Wegener or Smit Sibinga, only increases the difficulty of gaining a satisfactory conception of the development and present structure of the archipelago." Kuenen, however, is inclined to look with some favor upon a possible modified drift theory, but still considers the question an open one.

R. T. C.

Hot Springs of the Yellowstone National Park. By E. T. ALLEN and A. L. DAY. Washington: Carnegie Institution, 1935. Pp. xviii+525; figs. 215. $5.25 in paper; $6.00 in cloth.

To students of general geology, but especially to those interested in the problems of vulcanism and of ore deposition, this excellent monograph will come not only as the best description available for the region with which it specifically deals, but as a splendid contribution to the fundamental understanding of the fields mentioned. It represents the work of two very skilful students, and in addition the earlier work initiated by Hague, which was to have led to a monograph on the thermal activity of the Yellowstone Park.

Hot-spring discharges, temperature-depth relations, and gas contents of the hot springs were observed through the greater part of one summer. The difficulties attendant on discharge measurements alone, as covered in the fifth chapter, appear almost insurmountable. The rates of deposition of travertine and opal were measured by immersion of wooden cylinders, which became incrusted with the deposits. The rôle of microorganisms as agents of deposition has also been studied. And finally, the deposits have been examined microscopically, with the collaboration of Mr. H. E. Merwin.

The scope of the work becomes still more evident when it is realized that about three thousand springs are known to exist in Yellowstone Park —a number nevertheless smaller than that for Iceland or for New Zealand.

It is impossible in one short review to outline the many interesting facts and conclusions brought to light by the authors, but some at least may be listed. Nearly a hundred hot springs, for example, were found in

which the water was superheated—in some instances as much as 3° C.; indeed, in one case a temperature as high as 138° C. was recorded. The Yellowstone hot springs are inferred to result from circulating ground water heated by superheated magmatic steam that has risen along deep cracks; such steam is visible in several of the roaring jets, such as those in the Growler Basin; here, after heavy rainfall, a hot spring takes the place of the steam jets which appear in arid periods. In these cases, however, the water that ultimately comes to the surface would contain only small proportions of magmatic water (originally in the form of steam).

Two general kinds of hot springs are recognized—an alkaline type and an acid type. The chief dissolved constituents in the former are sodium-rich chlorides and bicarbonates; the relatively large sodium content is partly attributed to residual enrichment by differential removal of potassium, and in part to reaction with soda-rich rocks (e.g., rhyolites) through which the solutions passed. The acid waters are rich in sulphuric acid coming from the oxidation of sulphide solutions. This reaction is inferred to yield the greater heat that characterizes such solutions. Such an explanation opposes assigning the acid solutions to earlier, hence hotter, phases of volcanic activity.

The interpretation given above sheds an interesting light on at least three significant observations commonly derived from ore deposits. It suggests why barite frequently appears near the "high-temperature" end of ore deposition, preceded and followed, often in the same region, by sulphides. It also accounts for the sodium and calcium ions, which, combined with chlorine, have been found in inclusions in hydrothermal minerals. And it explains why sulphide ores frequently occur in limestones without noteworthy corrosion of the country rock—apparently because the depositing solutions had not yet been sufficiently oxidized to be highly acid.

The monograph illustrates admirably the highest grade of scientific work, in which carefully collected and assembled facts lead to conclusions of broad application to other phases of geology.

CHARLES H. BEHRE, JR.

"The Fauna of the Reefton Beds (Devonian), New Zealand," by R. S. ALLAN, in *Geological Survey of New Zealand Palaeontological Bulletin 14*. Wellington: G. H. Loney, 1935. Pp. 72; pls. 5. 3*s*.

The Lower Devonian Reefton beds of New Zealand and their fauna are described and well illustrated in this paper. Systematic descriptions

of the corals, bryozoans, brachiopods, mollusks, and crustaceans are supplemented by a chapter on the origin of this fauna. Faunal communities in England, France, Germany, South Africa, and the Americas are correlated with that of the Reefton beds, both in discussion and tabular form. Similar physical conditions, instead of actual faunal migration, are given by Allan as the reason for the remarkable similarity of the above-mentioned faunal communities in both the Lower and Middle Devonian. Paleontologists will be interested in this new contribution to the ecological phase of paleontology.

DAN J. JONES

Geology of the Oswegatchie Quadrangle. By NELSON C. DALE. New York State Museum Bulletin 302. Albany: University of the State of New York, 1935. Pp. 101; figs. 24; 1 map (in pocket).

Geology of the Berne Quadrangle. By WINIFRED GOLDRING. With a chapter on glacial geology by JOHN H. COOK. New York State Museum Bulletin 303. Albany: University of the State of New York, 1935. Pp. 238; figs. 72; 1 map (in pocket).

The geologic mapping of the Oswegatchie quadrangle completes the sixth of a series of nine quadrangles necessary to portray a cross section of the Adirondack pre-Cambrian area. Pre-Cambrian and Pleistocene formations only are represented, but the great complexity of rock types and structure and the high degree of metamorphism to which this area has been subjected have retarded the geologic interpretation of this important region. All igneous rocks recognized in the area intrude the oldest sediment, the Grenville; but their exact position in the pre-Cambrian column is unknown. Various metamorphic phases of the Grenville are mapped and described. The Oswegatchie area in the past has been economically important in the production of iron ore, but non-metallic products constitute the chief source of revenue at present.

Miss Goldring's presentation of the geology of the Berne quadrangle is praiseworthy because it is written to interest both the layman and the geologist. The Berne quadrangle includes the Indian Ladder country, a section of the Helderberg hills well known to geologists and the public. Geologists have visited this classic section for years, and now the public is enjoying the facilities of the John Boyd Thatcher Park. The report is largely stratigraphic and paleontologic in character, describing formations from Ordovician to Devonian in age. Many historical and geographic details lend an interesting touch to the geologic information given.

G. FREDERICK SHEPHERD